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# Industrial Waste Heat Recovery and the Potential for Emissions Reduction
## Volume 1. Main Report

Energy and Environmental Analysis, Inc.
Arlington, VA

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# INDUSTRIAL WASTE HEAT RECOVERY AND THE POTENTIAL FOR EMISSIONS REDUCTION,
## VOLUME 1: MAIN REPORT

by

Energy and Environmental Analysis, Inc.
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Project Officer

Benjamin L. Blaney
Energy Pollution Control Division
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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This report examines the applicability of conservation equipment to various industrial sectors, determines the net costs involved, and assesses the potential for conservation as a means of air pollution control. Predictions of the amount of waste heat available from U.S. industrial sources were made and a waste heat inventory was established. The inventory is segmented by industrial group, industry, process, and flue gas temperature. The waste heat recovery equipment analysis determined the costs and applications of a variety of waste heat recovery equipment. The analysis examined five major equipment types and their limitations. Cost functions were developed which used furnace flue gas flow rate and temperature, and air preheat temperature as inputs. A discussion of the major factors to be considered for the development of heat recovery equipment also is included. A discussion on the availability and development of high temperature burners and the effects of high preheat temperature on ancillary equipment is included. High preheat temperatures result in higher flame temperatures and correspondingly higher $NO_x$ emissions. This issue also has been addressed in this report. Volume 1 describes study methodology and findings. Volumes 2 through 10 tabulate stack gas waste heat inventories for all the industrial processes studied.

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## NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

# ABSTRACT

This report examines the applicability of waste heat recovery equipment to various industrial sectors, determines the net costs involved, and assesses the potential for waste heat recovery as a means of air pollution control. Predictions of the amount of waste heat available from U.S. industrial sources were made and a waste heat inventory was established. The inventory is segmented by industrial group, industry, process, and flue gas temperature. A description of the theoretical basis for the inventory, the method of execution, the limitations of the analysis, and the results are included.

The waste heat recovery equipment analysis determined the costs and applications of a variety of waste heat recovery equipment. The analysis examined five major equipment types and their limitations. Cost functions were developed which used furnace flue gas flow rate and temperature, and air preheat temperature as inputs.

A discussion of the major factors to be considered for the development of heat recovery equipment also is included. Since a major waste heat recovery technology involved preheating combustion air, a discussion on the availability and development of high temperature burners and the effects of high preheat temperature on ancillary equipment is included. High preheat temperatures result in higher flame temperatures and correspondingly higher $NO_x$ emissions. This issue also has been addressed in this report.

This report was submitted in fulfillment of Contract No. 68-03-2622 by Energy and Environmental Analysis, Inc. under sponsorship of the U.S. Environmental Protection Agency. This report covers the period October 25, 1977 to March 28, 1979 and work on this project was completed in October 1981.

# FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts of our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report describes the flue gas waste heat recovery potential for various industrial processes and the techniques available for recovering that thermal energy. The potential for emission reduction through waste heat utilization is discussed. This report should be useful to businesses and government agencies concerned with both energy conservation and pollution reduction. Further information on this subject may be obtained from the Energy Pollution Control Division of IERL-Ci.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

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# 1. INTRODUCTION AND SUMMARY

## 1.1 OBJECTIVES

This report investigates the various applications of energy conservation technologies which recover waste heat from furnaces, boilers, and tubestill heaters. The three main objectives are: (1) to characterize feasible conservation equipment for different industrial processes, (2) to determine how air pollution emissions may be changed by use of waste heat recovery equipment, and (3) supply a waste heat inventory.

### 1.1.1 Background and Scope

The development and use of waste heat recovery technologies may be limited by factors such as equipment and installation costs, fuel savings, and retrofit problems caused by plant size, high temperatures, and burner design. To determine the possible market penetration of a variety of recovery technologies, the effectiveness of the equipment, fuel savings, and costs were compared. The energy conservation technologies can vary from economically attractive to unattractive. The current availability of burners able to accept the high temperatures of waste heat recovery also will affect the marketability of the equipment. Pollution formation was studied to determine the effects of using waste heat recovery equipment and the resulting high temperatures on emission levels.

The five major components of energy conservation application and waste heat recovery discussed in this report are:

(1) Establishment of waste heat inventory (Section 2).

(2) Determination of feasible waste heat recovery technologies (Section 3).

(3) Determination of factors affecting waste heat recovery and equipment limitations, specifically in furnaces, ovens, and kilns (Section 4).

(4) Determination of compatibility between conservation equipment and available burner design (section 5).

(5) Determination of the effect of waste heat recovery devices on criteria pollutants with an emphasis on $NO_x$ emissions (Section 6).

### 1.1.2 Waste Heat Inventory*

The waste heat inventory was established to determine the amount of waste heat available from all non-evaporative sources. The flue gas heat loss from these sources was tabulated and then ranked by flue gas temperature so that higher temperature sources, which offer the largest savings, could be identified readily.

The waste heat inventory is based on the Environmental Protection Agency's (EPA) National Emission Data System (NEDS) which examines both large and small sources. This data base provides the best available information on industrial sources in the U.S. and reports stack temperatures and flue gas flow rates. To develop the waste heat inventory, NEDS was adapted by performing theoretical calculations based on the flue gases from several fossil fuels at various fuel/air ratios. Next, functions for energy per unit volume of flue gas were developed. From this information, a second set of functions was developed for the maximum, minimum, and expected waste heat values.

### 1.1.3 Waste Heat Recovery Technologies

Based on the information found in the waste heat inventory, the appropriate waste heat recovery equipment for the industrial sources with available waste heat was determined. Two broad classes of waste heat recovery equipment exist: (1) those the preheat combustion air, and (2) those that heat the product. Section 3 examines five major equipment types within these two classes: (1) recuperators and (2) regenerators for furnaces, (3) economizers for boilers, and (4) tubular convection sections and (5) air preheaters for tubestill heaters.

Information concerning feasible conservation technologies was obtained from past and potential users as well as equipment vendors. Mathematical models of the heat and mass flows in the air preheat equipment then were developed and checked against vendor supplied performance data. Similar models also were developed for economizers. Air preheat as well as product heating were considered for tubestill heaters in the petroleum and chemical industries. Case studies were used to focus on complex energy use problems of these two industries.

### 1.1.4 Waste Heat Recovery Limitations

Section 4 of this report focuses on the limitations of waste heat recovery and the factors affecting its use in furnaces, ovens, and kilns. Due to their high temperatures and typically high fuel consumption rates, these devices generally are regarded as prime candidates for the use of preheated combustion air. Unfortunately, their wide range of designs and site-specific application make it almost impossible to define a typical furnace or to consider just the factors which determine equipment and installation costs without obtaining site-specific engineering information.

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* Volumes 2 to 10 of this final report present the inventory of waste heat available from flue gases.

There are, however, a number of general factors which can affect the use of recovery equipment in most situations. These factors include available space, temperature ranges, pollution control equipment, and fuel consumption as well as a variety of other factors. Even though these limiting factors may affect conservation equipment development, waste heat recovery is still considered feasible.

### 1.1.5 Burner Availability and Design

The most promising energy conservation technology for many applications is increasing the combustion air temperature. Until now, the effect of this increase on industrial burners has been unclear. Section 5 discusses the effect waste heat recovery has on burners, as well as burner availability from manufacturers when the use of preheat air is desired. Since many flame shapes and burner sizes are available, it was necessary to examine various potential applications. This component established the availability of burners using high temperature air by contacting vendors to determine if they would sell and guarantee the performance of the burners.

### 1.1.6 Environmental Impact

The final components of Volume I was to assess the impact of combustion air preheat on emissions of total suspended particulate mattter (TSP), sulfur dioxide ($SO_2$), and nitrogen oxide ($NO_x$). The change in fuel consumption with combustion air preheating was determined, in order to estimate the reductions in TSP and $SO_2$ which might result from this application of waste heat recovery.

Nitrogen oxide emissions may be affected adversely by the application of the waste heat recovery devices. The focus of Chapter 6 is on the formation of thermal $NO_x$ after the installation of waste heat recovery devices. A thermal $NO_x$ model was developed to estimate the amount of NO formation and $NO_x$ emissions by studying the temperature, concentration of reactants, and residence time of the flue gases.

## 1.2 SUMMARY OF PROJECT FINDINGS

The waste heat inventory reveals that 14.9 exajoules (14.1 quads) energy were released from all non-evaporative sources reported in the National Emissions Data System (NEDS) file in 1974. Even though this is a considerable amount of heat released in flue gases, most is below 149°C (300°F) which is considered the operational minimum for heat recovery from the combustion of fossil fuels containing sulfur. Therefore, most waste heat is too low to recovery for useful work, leaving only 1.6 EJ available in most applications.

In general, the waste heat inventory results are good estimates of the waste heat produced in the United States. The inventory is especially valuable in assessing the relative potential for recovery in the Standard Industrial Classifications (SIC's) and enables specific industrial processes within a SIC to be investigated. The inventory indicates the largest waste heat producer is utilities (SIC 49) which releases 6.1 EJ The combined waste heat from numerous manufacturing sources (SIC 20 to 39) is 7.3 EJ Only

1.6 EJ of this total are available for use, assuming flue gases are cooled only to 149°C. Utilities contribut 0.5 EJ and manufacturing 1.1 EJ The amount of usable waste heat from utilities is less because the temperature is too low, while a higher percentage of manufacturing waste heat can be used since it is above 149°C.

This higher percentage of available heat indicates that the prospects of recovering waste heat are better for manufacturing industries than utilities. Within the manufacturing industries, the best recovery potential is in: (1) refining (SIC 29), (2) stone, clay, and glass manufacturing (SIC 32), (3) primary metals (SIC 33), and (4) fabricated metals (SIC 34). This assessment is based on the relatively high percentage of available heat in these industries in addition to the high gross values for the amount of heat released. Figure 1 shows the expected waste heat for all SIC's. The final results for the inventory are presented in Table 1 and Figure 2 where the waste heat inventory is categorized by flue gas temperature at the time of release.

Five technologies which recover usable waste heat were analyzed in this report and appear to be the most feasible application for their respective industries. Recuperators and regenerators are the two best combustion air preheat technologies for furnaces. These methods are generally proven techniques for saving energy, and the necessary equipment is sold be a variety of manufacturers. The most efficient recovery method for boilers is economizers which transfer heat to the cold feedwater. Economizers were preferred by most industrial boiler users. For petroleum refining furnaces, convection sections that heat hydrocarbon liquids, and air preheat technologies were both investigated. They also were considered the best available technologies for tubestill heaters.

Generally, unfavorable economics limit the market penetration of most heat recovery equipment, with equipment marketability only occurring when there is a desire for fuel savings or lower costs. In times of high demand, production is the most important factor and energy efficiency is relatively immaterial. However, in the absence of any unusual barriers, an operator will invest in heat recovery equipment if the fuel savings can achieve the required investment return on his capital. One justification for investing in recovery equipment is concern over fuel availability and rising fuel costs. If significant problems with fuel availability are foreseen, then the equipment investment can be justified to insure that the furnace will maintain production at or near regular levels, even if fuel supplies are reduced. Investment in heat recovery equipment still depends on how crucial the furnace's production is to the manufacturer's profitability. Energy conservation is usually not considered a goal in itself, but simply one of many ways of lowering operating costs. Often, it is used only when product demand is low and costs must be trimmed. When this occurs or when there is a need for fuel savings, there will be market penetration by heat recovery equipment.

The major benefits of installing waste heat recovery equipment are fuel savings and production increase. Since users typically do not include productivity increases in the economic evaluation of waste heat recovery equipment

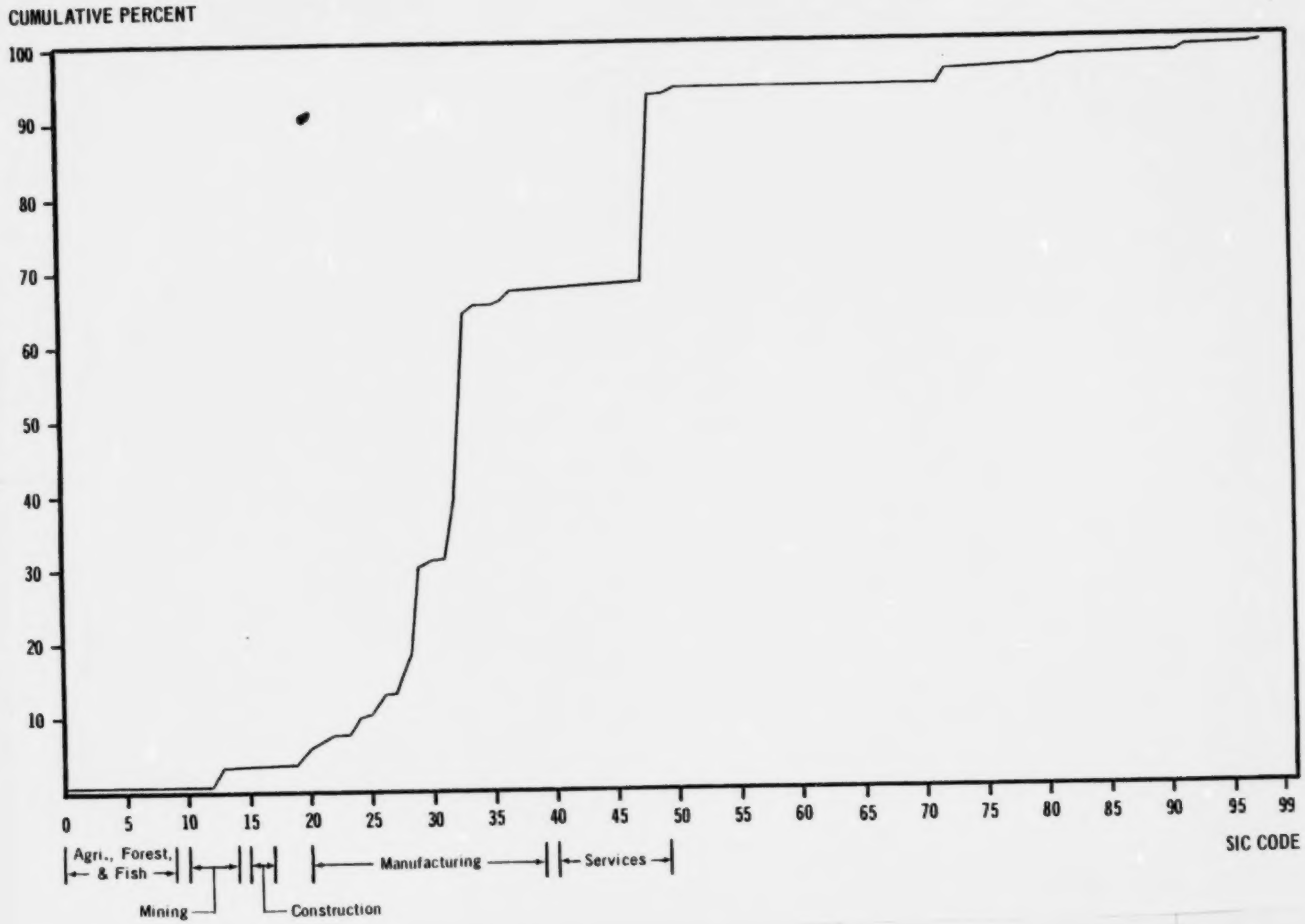

Figure 1. Cumulative expected waste heat by SIC, 149°C base.

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TABLE 1. TOTAL WASTE HEAT INVENTORY (QUADS)

SIC 1-99

| | All Facilities | Facilities With Pollution Control | Facilities Without Pollution Control |
|---|---|---|---|
| Maximum | | | |
| 16°C Base* | 17.9 | 8.8 | 9.1 |
| 149°C Base | 1.6 | 0.4 | 1.2 |
| Expected | | | |
| 16°C Base | 14.1 | 6.9 | 7.2 |
| 149°C Base | 1.6 | 0.4 | 1.2 |
| Minimum | | | |
| 16°C Base | 5.8 | 3.2 | 2.6 |
| 149°C Base | 0.9 | 0.3 | 0.6 |

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* Base temperatures are enthalpy reference temperatures. Note: 16°C = 60°F and 149°C = 300°F.

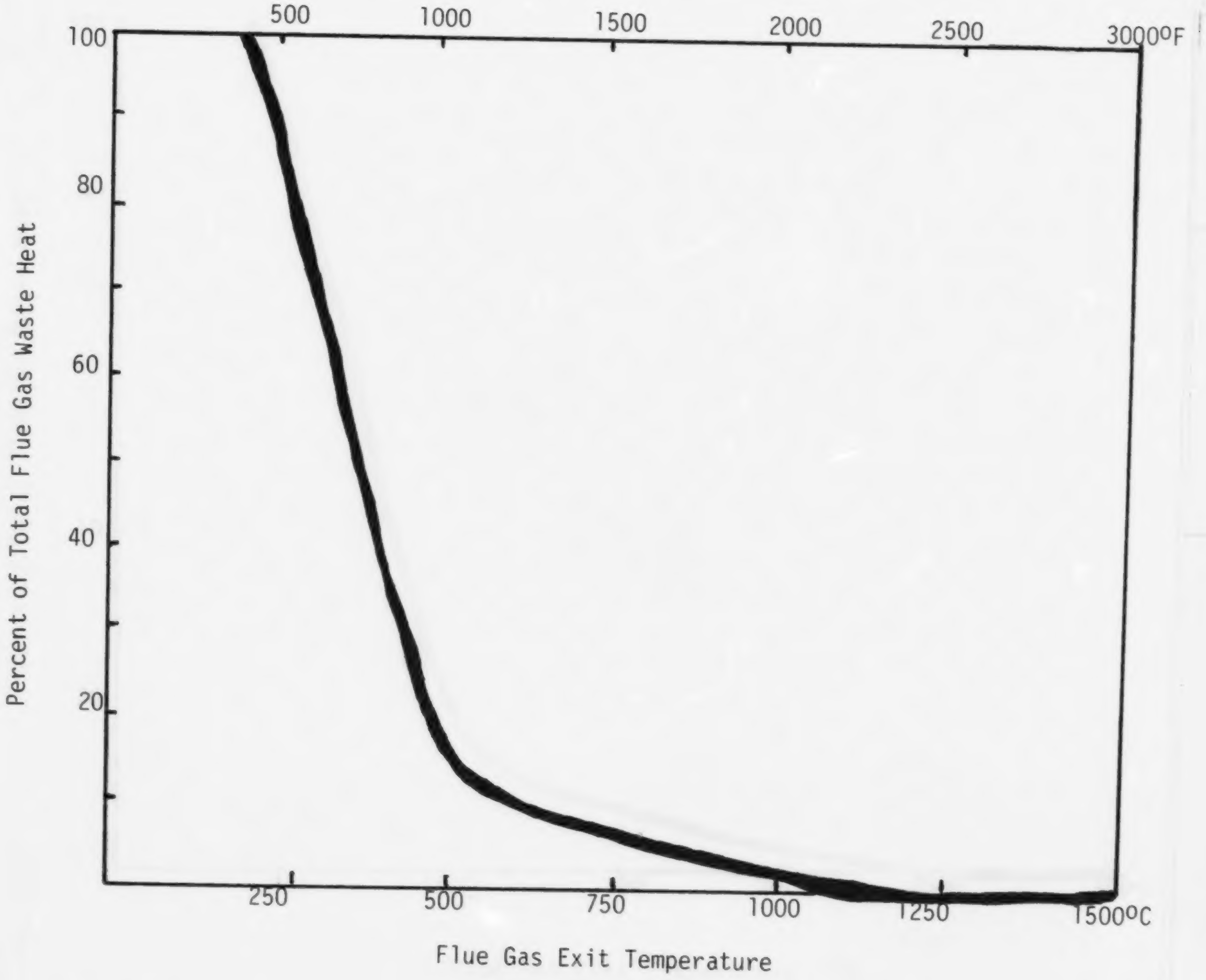

Figure 2. Expected waste heat: cumulative temperature totals (149°C reference temperature).

only fuel savings were considered in this report. The amount of fuel saved is directly proportional to the preheat temperature. Doubling the preheat temperature will roughly double the fuel savings; however, equipment costs are likely to more than double, especially as the temperature reaches the upper limit of the attainable preheat levels. For some furnaces the fuel savings can be over 30 percent.

Since the fuel savings depends upon the exhausted flue gas temperature, the high temperature recovery recuperators offer the largest savings. Recuperators also endure the most rigorous operating conditions so their equipment is the most expensive. In many cases the less efficient unit saves a given amount of fuel for a smaller cost. Table 2 presents the costs of the equipment and the approximate fuel savings for different types of heat recovery equipment.

Cost restrictions of waste heat recovery equipment are dependent on equipment type and installation costs. Since each unit has a maximum attainable preheat temperature, the equipment cost rises rapidly as the maximum temperature is approached. For example, using combustion air preheat requires the use of expensive alloys as construction materials. The high temperatures also affect installation, thus raising total costs. In a good application the installation cost will be about twice the equipment cost. In uneconomical situations, however, installation cost can be as much as 12 times the equipment cost.

In general, the design and material limitations of using recovery equipment are dependent on temperature and flue gas contaminants. Combustion air preheat is limited by temperature and this temperature, as well as existing recuperator design, affect fuel savings so that savings over 40 percent are not easily achieved. Leaks between the air and flue gas sides also limit the equipment's performance. Some recuperator designs foul with dust deposits or other contaminants; this is especially serious for unit glass melters, such as fiberglass manufacturing, and for metal heating applications where scale is carried out of the furnaces. Oxidation and sulfur attack the materials and cause corrosion which limits the use of certain construction materials. Corrosion can be prevented by upgrading the quality of the construction material frequently. However, this results in capital cost increases.

Since the burner designs technically are able to withstand high temperatures, it appears the major limitation in high temperature burner development and retrofit applications is the lack of product demand, difficulty in obtaining construction materials, and burner installation. This low demand is further compounded by diminishing fuel savings which occur beyond the optimum high temperature range. Preheat combustion equipment demand also is linked closely to the demand for waste heat recovery equipment. The use of this recovery equipment usually is limited by unfavorable economics.

Sulfur dioxide and particulate emissions will be reduced as a result of reduced fuel consumption associated with waste heat recovery. In the case of combustion air preheat in gas furnaces, reductions in emissions of these pollutnats could be up to 20% if preheated air temperatures are on the order of 540°C (1000°F).

## TABLE 2. TYPICAL FLUE GAS HEAT RECOVERY EQUIPMENT

| Furnace Type | Firing Rate, J/hr(MMBtu/hr) | Flue Gas Temp., $^oC(^oF)$ | Air Preheat Temp., $^oC(^oF)$ | Capital [2/] Cost ($1000) | Theoretical Fuel Savings (%) |
|---|---|---|---|---|---|
| Recuperators (Furnaces) | | | | | |
| Convection: | | | | | |
| Batch Forge | 42.2 (40.0) | 820 (1500) | 540 (1000) | 110 | 25 |
| Batch Reheat | 57.5 (54.5) | 980 (1800) | 540 (1000) | 120 | 34 |
| Continuous Reheat | 262.7 (249.0) | 1090 (2000) | 430 (800) | 280 | 26 |
| Radiation: | | | | | |
| Batch Melt | 35.9 (34.0) | 1090 (2000) | 430 (800) | 143 | 26 |
| Reheat Forge, Soak | 33.4 (31.7) | 1200 (2200) | 430 (800) | 76 | 29 |
| Continuous | 19.4 (18.4) | 1390 (2500) | 670 (1250) | 201 | 46 |
| Preheaters (Tubestill Heaters) | | | | | |
| Air Preheat | 110.8 (105.0) | 440 (815) | 340 (650) | 1,000 | 16 |
| Steam Generation[3/] | 2057[4/]-3165 (1950-3000) | 540 (1000) | 370 (700) | 12,000 | variable[4/] |
| Economizer (Boilers) | | Feedwater Outlet Temperature | | | |
| Oil/Gas-Fired Boiler | 184 (175) | 370 (700) | 170 (330) | 98.5 | 10.0 |
| Coal Fired Boiler | 343 (325) | 290 (550) | 140 (285) | 201.5 | 6.25 |
| Oil/Gas-Fired Boiler | 95 (90) | 320 (600) | 150 (300) | 52 | 7.5 |

---

[1/] Firing Rate is before recuperation.

[2/] Cost is in 1978 dollars and is the installed equipment cost.

[3/] A 15,890 $m^3$/day (100,000 bbl/day) refinery, with 20 furnaces exhausted through a steam generating waste heat boiler into a common stock.

[4/] Depending upon the magnitude of heat recovery supplied with the furnaces.

[5/] Steam at 4.48 MPa (650 psig).

[6/] Assuming inlet temperature to be 100°C and outlet temperature of flue gas to be 149°C.

There is little effect of combustion air preheat on fuel NO$_x$ formation; other studies have found that a small decrease in fuel NO$_x$ occurs with increase in combustion air temperature and reduced fuel consumption. This decrease is usually small in absolute magnitude compared to changes in thermal NO$_x$ with combustion air temperature.

There is only a gradual increase in thermal NO$_x$ with increasing flame temperature up to 1790$^{o}$C (3250$^{o}$F). Above this flame temperature, thermal NO$_x$ formation increases rapidly and approximately linearly with temperature up to about 1950$^{o}$C (3550$^{o}$F), where it reaches a maximum. However, most furnaces and boilers do not operate at air preheat temperatures which result in such high flame temperatures. Combustion air temperatures must be well above 540$^{o}$C for flame temperatures of 1750$^{o}$C to be reached. Therefore it is not expected that the increases arising from combustion air preheat will generally cause NO$_x$ emission increases of 100 ppm to occur. The exception will be those industries which operate at process temperatures at or above 1360$^{o}$C (2500$^{o}$F.)

## 1.3 LIMITATIONS OF STUDY

The NEDS data file was used to develope a waste heat inventory because it provided combustion gas data for the largest number of U.S. industrial sites. However, the use of the NEDS data file resulted in one significant limitation to the investory and several areas of uncertainty.

The available waste heat listed in the inventory is lower than what actually may be obtained from an industrial process because the temperatures used to calculate gas waste heat contents were obtained at the stack, not at the exit to the combustion device. There is often a drop of several hundred degrees between the temperature of combusted gases leaving the combustion device and the flue gas temperature. An even greater temperature differential is likely to exist if there is pollution control equipment in the gas stream. Therefore, the inventory presented in this report reflects a lower limit to available waste heat.

The use of NEDS data introduces several uncertainties to the inventory. These are briefly described here; they are discussed in greater detail in Section 2. First, NEDS provides information about the composition of pollutant gases and particulates in the flue gas stream, but usually does not indicate the amounts of gases present which are not pollutnats, such as water and N$_2$. Therefore, assumptions had to be made about stack gas composition in order to calculate waste heat content. Second, there were random inaccuracies in the NEDS data base. Extensive screening was performed on the NEDS file before calculating the inventory, and most, if not all, of the major or consistent errors were removed. Therefore, the random inaccuracies which occurred in the data base should not affect the results significantly. The final problem with the data base was the exclusion of sources from the file because data on these sources was incomplete or obviously wrong. In cases where reasonable data values could not be determined, all data for the source were dropped. Deletion of this information lowers waste heat totals. However, there were only a limited number of industrial

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processes - identified in the text - where such deletions may have significantly affected estimates of total recoverable waste heat.

Some inconsistencies were noted during the discussions which were carried out with vendors of waste heat recovery equipment. Vendors will, of course, try to present their equipment in the best light. The authors of this report used their best engineering judgement in incorporating the information suppled by vendors into the analysis of waste heat technologies in Sections 3 through 5.

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# 2. WASTE HEAT INVENTORY*

## 2.1 INTRODUCTION

To evaluate the efficiency of fossil fuel use, as well as the potential energy conservation benefits of heat recovery, the amount of waste heat available from U.S. industrial sources was estimated. This chapter discusses the waste heat inventory development and describes its theoretical basis, the methodology, the limitations of the analysis, and the results.

## 2.2 PROCEDURE

The waste heat inventory represents the sensible heat contained in flue gases emitted from all non-evaporative sources in the U.S. These sources are compiled in the National Emissions Data System (NEDS) which is the result of a nationwide survey of all emission sources.

### 2.2.1 Theoretical Basis

The project objective was to determine the enthalpy, or heat content, of the gases exiting from industrial processes. These gases at exit temperatures were compared to the same gases at standard reference temperatures. The difference between the two temperatures is known as waste heat. In this study, two standard reference temperatures were used. First, a total inventory of all the waste heat released was established with a reference temperature of $60^{o}$F ($16^{o}$C). Sixty degrees was selected because it represents the theoretical minimum temperature at which the flue gases have any heating value. The second reference temperature was set at $300^{o}$F ($149^{o}$C) and represents the available inventory or heat which can conceivably be recovered to do useful work in industrial processes. Three hundred degrees is considered the operational lower limit for heat recovery from the combustion of fossil fuels containing sulfur. Below $300^{o}$F the flue gas temperatures are too low to provide good heat transfer. In addition, the dew point of sulfuric acid in flue gas is between $280^{o}$ and $300^{o}$F ($138^{o}$ and $149^{o}$C) and operating a heat recovery device is difficult, if not impossible, in a condensed sulfuric acid atmosphere due to increased deterioration from the acid.

To calculate the change in enthalphy from the base value, the gas pressure, temperature, and composition must be defined. This analysis assumes that all flue gases are at atmospheric pressure, since most industrial processes operate at or near atmospheric pressure. Temperature can be easily established from current literature; however, the temperatures in NEDS are measured at the stack exit instead of the furnace exit which is inappropriate for a waste heat inventory. Since NEDS contains the best available information on stack temperatures, it has been adapted to establish the waste heat data base. To determine flue gas composition, four categories were investigated:

---

* This chapter describes the process used to derive a waste heat inventory. The methodology was based on English units. Therefore, the chapter is in English units, with metric units provided in parenthesis, where appropriate.

- dry flue gas
- water vapor
- unburned hydrocarbons
- particulate emissions (solids)

Separate calculations for each component were performed, thereby establishing a total waste heat value for each source. This total can be tabulated by industry, flue gas temperature, or any other category which might be useful.

The total enthalpy is the sum of the enthalpies of all the components in the dry flue gas. Equations for the specific heats of typical flue gas components ($CO_2$, $N_2$, $O_2$, CO, $CH_4$, $H_2$, NO, $SO_2$, and others) can be found in standard thermodynamic texts and chemical handbooks. The enthalpy of the dry flue gases can be calculated from the relation:

$$H_t = M_i \int_{T_r}^{T_i} C_{pi} \, dT \qquad (1)$$

where $C_{pi}$ = Specific heat of component i; heat per unit mass per unit temperature, degrees

$H_t$ = Total enthalpy, heat per unit mass

$M_i$ = Fraction of dry flue gas which is component i, dimensionless

$T_i$ = Flue gas exit temperature, degrees

$T_r$ = Reference temperature, degrees

The enthalpy change in the flue gas water can be found in the Steam Tables and does not need to be calculated. However, partial pressure of water vapor, used in determining the water enthalpy, must be calculated.

The heat content of any unburned hydrocarbons in the flue gas streams can be divided into two parts: the sensible heat and the chemical energy that would be released if the volatiles were combusted. The sensible heat is accounted for in the dry flue gas calculations. The chemical energy was not calculated in this analysis because unburned hydrocarbons either evolve as a process by-product or are the result of inefficient combustion practices. Hence, the chemical energy is not considered waste heat since energy could be released only by modifying the combustion process which causes the volatiles not to enter the flue gas stream.

The heat content of particulate matter in flue gas streams can be dealt with in much the same way as the dry flue gases, by simply calculating mass specific heat change with temperature. For solids in fossil fuel combustion gases, it is reasonable to assume a value of:

$$\text{Cp (solid)} \cong 0.165 \text{ Btu/lb} \cdot {}^{\circ}\text{F} = 691 \text{ J/kg} \cdot {}^{\circ}\text{K} \qquad (2)$$

for the specific heat at all temperatures considered here.

### 2.2.2 Data Base

The NEDS data base provides the best available information on industrial sources in the United States. The file reports stack temperatures and flue gas flow rates but does not report flue gas composition since it is not used for most emission work. The information available from NEDS required adaption in order to develop the waste heat inventory. To adjust the data base, theoretical calculations based on the flue gases from several fossil fuels at various fuel/air ratios were made following the method used to determine solids in fossil fuel combustion gases (see Table 3 ). Functions for Btu's per actual cubic foot of flue gas were developed from the calculation results assuming ideal gas behavior (see Figures 3 and 4 ). From this information a second set of functions was developed for the maximum, minimum, and expected waste heat values (see Figures 5 and 6 ). In these calculations, the heat content of solid particles was disregarded since their gross heat value is low compared to the heat value of dry flue gases and water vapor. Moreover, it is questionable whether the particles would transfer heat efficiently during the limited time in the heat recovery device due to the thermal limitations of solid particles.

The waste heat for a specific source was calculated from the temperature and the stack flow rate data. Six enthalpy values were assigned to each source. These values, minimum, maximum, and expected, all at 60 and 300°F (16 and 149°C) were based on the theoretically developed functions. Based on the stack flow rate of the source, six heat values were calculated by multiplying the flow rate (actual cubic feet per year (acf/yr)) by the enthalpies (Btu/acf). These heat values were then placed in the appropriate temperature range, Source Code Classification (SCC), and two digit Standard Industrial Classification (SIC). The waste heat calculations are on a yearly basis and all inventory results are expressed in Btu's/year.

## TABLE 3. SAMPLE FLUE GAS ANALYSIS

| Fuel | Fuel Composition | Flue Gas Composition, volume % | | | |
|---|---|---|---|---|---|
| | Weight % | | % Excess Air | | |
| Coal (Ohio Bit.) | | | 0 | 50 | 100 |
| | C = 72.0 | | | | |
| 13,250 Btu/lb | $H_2$ = 4.4 | $CO_2$ | 16.56 | 11.20 | 8.46 |
| (29.57 MJ/kg) | S = 1.6 | $H_2O$ | 9.19 | 6.87 | 5.70 |
| | $O_2$ = 3.6 | $SO_2$ | .14 | .09 | .07 |
| | $N_2$ = 1.4 | $N_2$ | 74.11 | 75.18 | 75.70 |
| | $H_2O$ = 8.0 | $O_2$ | 0 | 3.57 | 10.07 |
| | Ash = 9.0 | | | | |
| Oil (No. 2) | Weight % | | | | |
| 140,000 Btu/gal | C = 87.3 | | | | |
| (39 GJ/$m^3$) | H = 12.6 | $CO_2$ | 14.42 | 9.81 | 7.43 |
| | S = .22 | $H_2O$ | 14.18 | 10.35 | 8.37 |
| | O = .04 | $SO_2$ | .14 | .09 | .07 |
| | N = .006 | $N_2$ | 71.27 | 72.75 | 73.50 |
| | Ash = .01 | $O_2$ | 0 | 7.00 | 10.63 |
| Natural Gas | Volume % | | | | |
| 985 Btu/scf | $CH_4$ = 93.27 | | | | |
| (36.7 MJ/scm) | $C_2H_6$ = 3.79 | $CO_2$ | 9.54 | 6.56 | 5.00 |
| | $C_3H_8$ = .57 | $N_2$ | 70.21 | 72.44 | 73.63 |
| | $C_4H_{10}$ = .29 | $O_2$ | 0 | 6.42 | 9.78 |
| | $CO_2$ = .79 | $H_2O$ | 20.25 | 14.58 | 11.59 |
| | $N_2$ = 1.19 | | | | |

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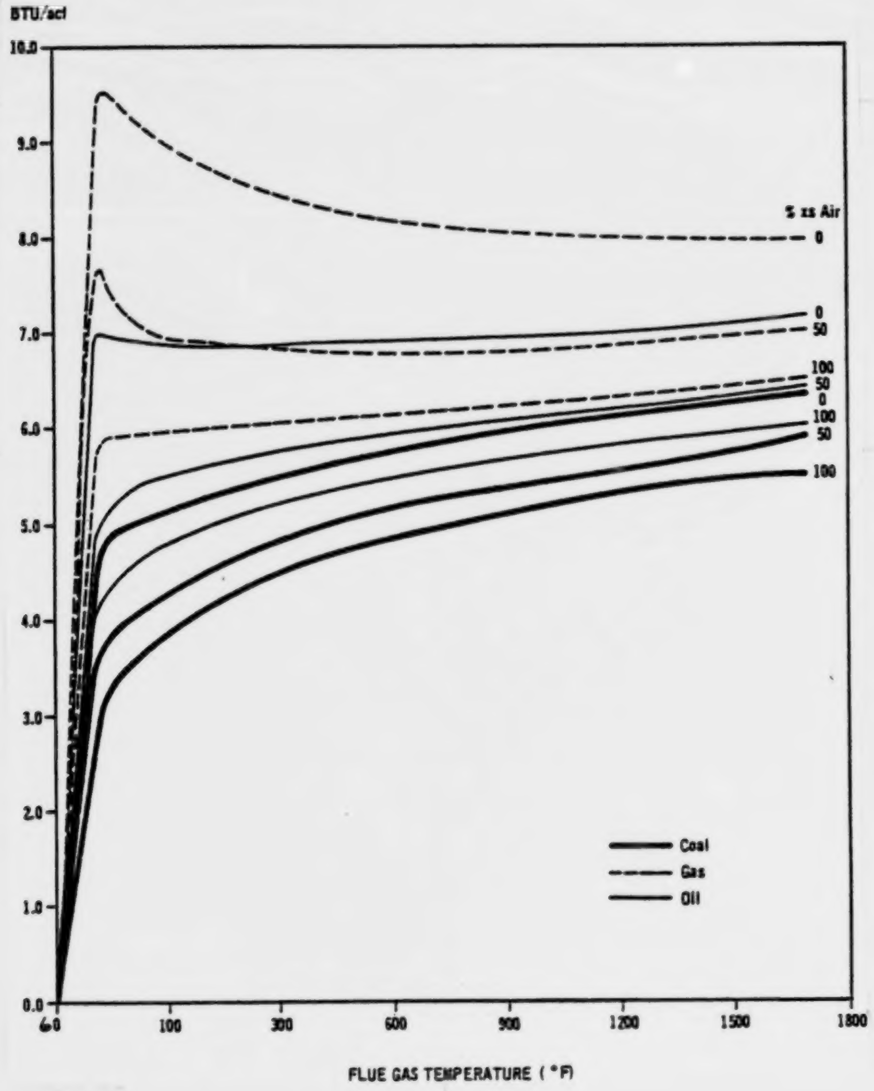

Note:
$^{o}C = (^{o}F-32)/1.8$
1 J/acm = $2.7 \times 10^{-5}$ Btu/acf

Figure 3. Flue gas enthalpy (60°F (16°F) reference).

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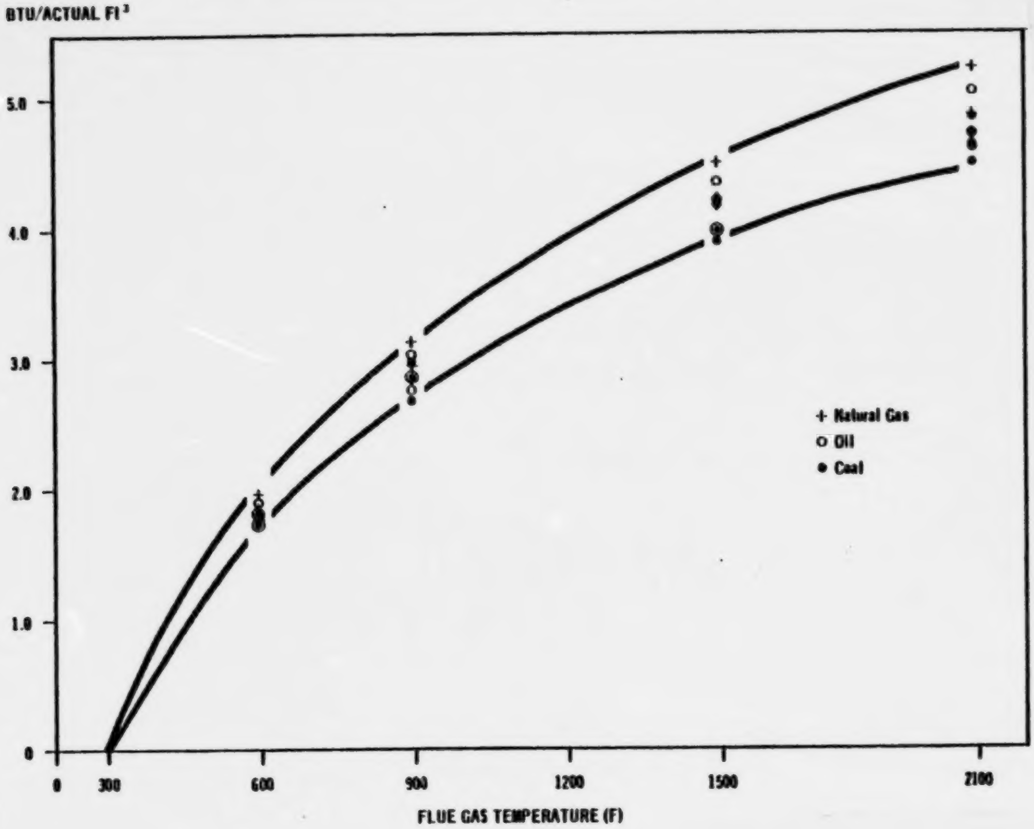

Note:
$^oC = (^oF-32)/1.8$
1 J/acm = $2.7 \times 10^{-5}$ Btu/acf

Figure 4. Flue gas Enthalpy (300°F (149°C) Reference).

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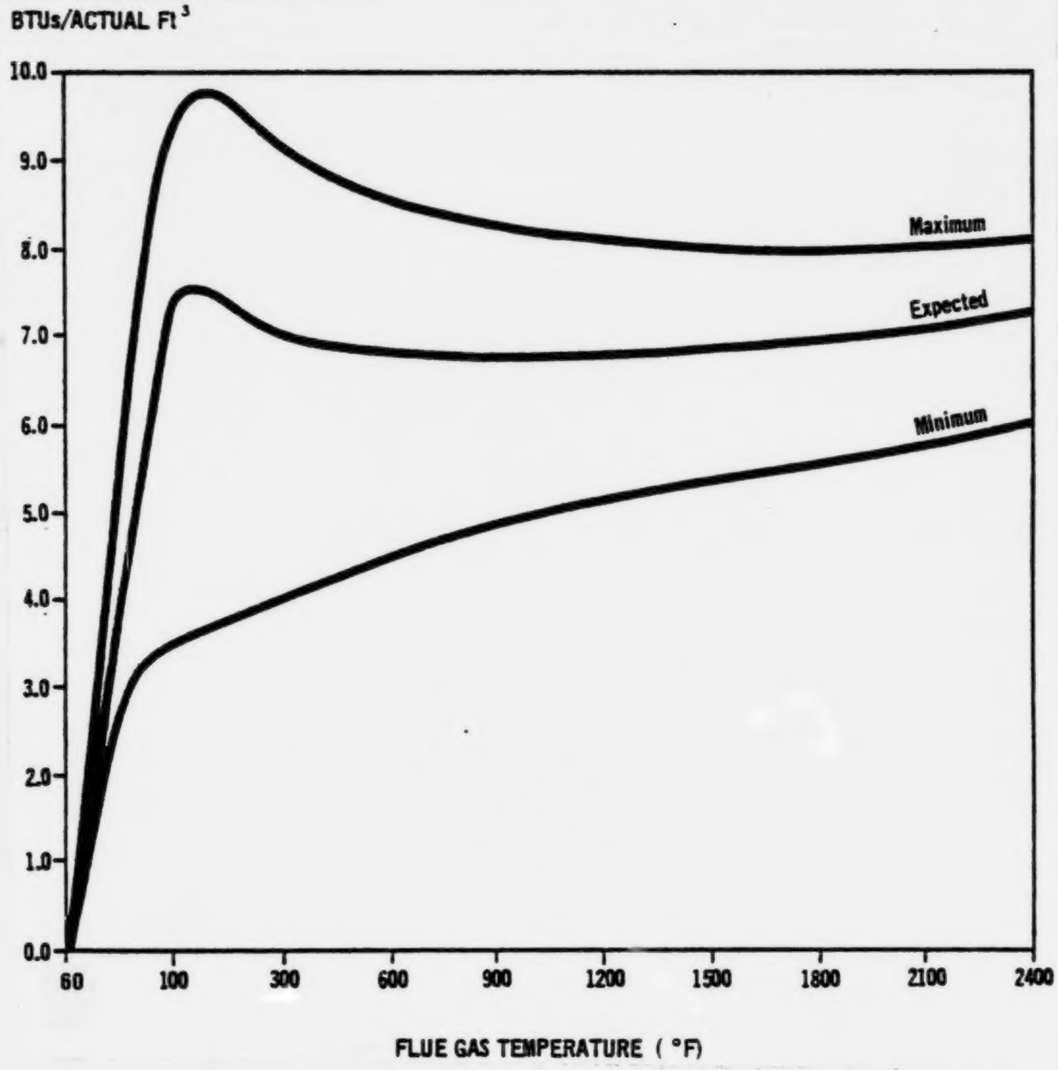

Note: $^{o}C = (^{o}F-32)/1.8$
$1 \text{ J/acm} = 2.7 \times 10^{-5}$ Btu/acf

Figure 5. Enthalpy curves for Waste Heat Inventory ($60^{o}(16^{o}C)$ reference).

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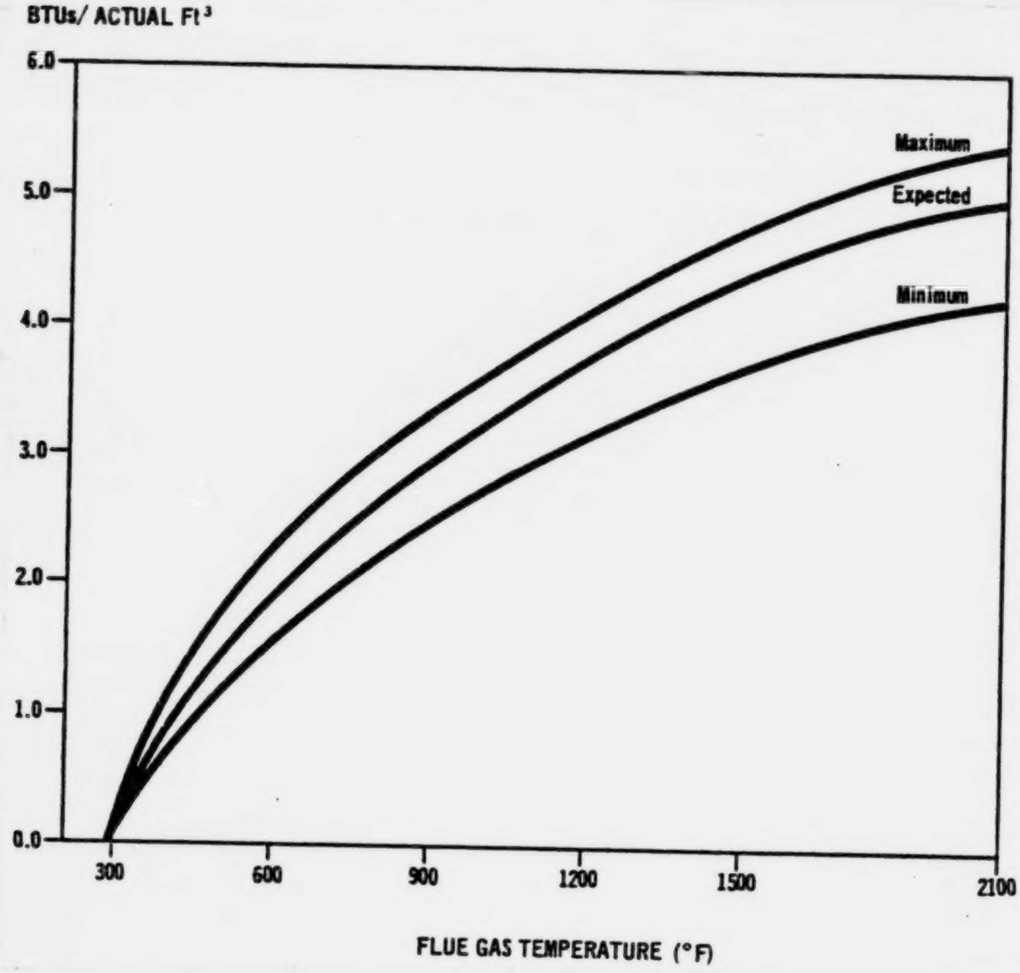

Note:

$^\circ$C = ($^\circ$F-32)/1.8
1 J/acm = 2.7 x $10^{-5}$ Btu/acf

Figure 6. Enthalpy curves for Waste Heat Inventory (300$^\circ$F (149$^\circ$C) reference).

### 2.2.2.1 Source of Data

The NEDS data base is an emission source survey conducted by EPA to establish baseline information on pollution sources in the United States. The data base is classified by SCC. This classification method is appropriate for the analysis since it groups facilities by a specific process or operating procedure. However, any system set up in such a way is subject to several weaknesses resulting from the great diversity of design in industrial operations. Weaknesses include grouping similar processes to achieve different ends as well as grouping processes which are dissimilar but have the same function. Even with these weaknesses, an SCC system is much more valuable than an SIC system, since an SCC system divides the industries into various processes while the SIC system groups all processes together, even though they may have different waste heat potentials. Since energy consumption data is organized by the SIC method, an assessment of fuel use efficiency requires that waste heat information be presented in the same form. The SIC classification for each source is available from the NEDS file.

### 2.2.2.2 Adjustments and Data Validation

The NEDS surveys were completed by plant personnel and, for the most part, were not checked for accuracy before they were entered in the file. This method of data collection is subject to several errors: (1) incorrect or inconsistent interpretation of the survey questions, (2) lack of any response about certain facilities, (3) unknowledgeable or uncooperative respondents, and (4) errors in data transmission.

The accuracy of the waste heat totals critically depends on the accuracy of stack flow rates and temperature entries. Therefore, considerable effort was expended to transform the NEDS file into its best possible form for calculating the waste heat inventory.

In order to verify temperature data, the NEDS file was screened to locate and exclude the SCC's with temperatures outside the zero to 3000°F (-20 to 1650°C) range. Histograms then were developed for all points within the range in order to show the frequency of temperature entries in each 100°F (38°C) section from zero to 3000°F. Because pollution control equipment can significantly lower flue gas temperature, each SCC was divided into two groups: sources with pollution control equipment and sources with control equipment. Few pollution control devices can handle flue gas temperatures above 750°F (400°C), so some processes must cool flue gases prior to entering the control equipment. This division also can serve to help identify which entries with control equipment have temperatures outside the range of feasible operation.

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The temperature analysis revealed temperatures in the file as high as 9559°F (5293°C) and as low as -80°F (-62°C). All temperatures outside the range of zero to 3000°F were found to be incorrect based on their associated processes. Each SCC division then was examined to determine default temperatures. These default temperatures represent the most typical temperatures for the SCC. Each SCC was screened for specific temperatures. If the reported temperature for an entry fell outside the reasonable range for the SCC, the temperature then was assigned the default value. The temperature histogram for the zero to 3000°F range allowed explicit analysis of virtually every temperature entry in the file. Because less than one percent of the entries required default values, it is highly unlikely that any irregular entry in the file caused distortion in the calculation of the waste heat inventory.

Verifying the stack flow rate data in the NEDS file was much more difficult than verifying the temperature data. Stack flow rate is a function of operating rate, plant design, and process, and varies much more between facilities than temperature, which is related directly to process requirements.

The most crucial factor affecting stack flow is the operating rate. For this reason, the primary stack flow analysis model in the file compares production rate to stack flows adjusted for temperature and operating rate. Production rates are reported in SCC units per year, which are usually tons of product produced or amount of fuel consumed. Each SCC code has different SCC units. For example, if the SCC units are fuels consumed (coal, oil, or natural gas), they are converted into MMBtu consumed in order to compare various SCC's. To be consistent with production rate data, stack flow rates also were reported on a yearly basis. This was done by adjusting the NEDS stack flows for each source from acf/minute to standard cubic feet per year (scf/yr) based on temperature and operating schedule, i.e., hours/day, days/week, and weeks/year. For the temperature adjustment, the ideal gas law was assumed to be valid. The adjustment of the flow rates to standard conditions alleviated problems inherent in attempting to compare gases at different conditions, hence, at different densities.

For each SCC, both with and without control equipment, plots of stack flow (scf/yr) versus production rate (SCC units/year) were developed. A least squares regression was then run on each plot. In many SCC's, the entries at the high end of either the production rate or flow rate scale skewed the regression line towards them. This resulted in many points being excluded from the field and reduced the accuracy of the regression line. To avoid this problem, sources outside two standard deviations from the regression line were identified as plants which are either operating far outside what is considered normal practice or entries that are the result of improper or inaccurate reporting. A second regression then was run on the remaining points in the field. The line resulting from this regression was used to calculate default values for points which did not lie within reasonable operation ranges. If both the stack flow and the production rate were outside two deviations from their mean, then the stack flow rate for the SCC division was defaulted. If the production rate was within two standard deviations from the mean, but the flow rate was outside two standard deviations, then the stack flow rate was set at the value predicted by the regression line for the reported production rate. If a source's stack flow rate was within two standard deviations of the mean for the SCC, the reported value was maintained.

It was assumed that production rate is among the most accurately reported parameters in the file since manufacturing facilities have more information concerning production rate or fuel consumption than stack gas flow rates, thereby producing more reliable results. The correlation coefficients of these regression lines remained quite low in many cases. A simple least squares regression proved to be somewhat inappropriate for the stack flow rate and production rate file data. Regression lines represent good approximations for an SCC, but cannot be expected to be valid for a specific facility since they are only estimates.

After infeasible stack flows were corrected, all stack flows were readjusted into actual cubic feet per year (acf/yr) so they would be in the appropriate form for waste heat calculations. Again, this conversion was based on the assumption of ideal gas behavior.

If there was a zero flow rate or temperature entry in the file indicating a blank entry in the data base, the entry was left at zero for calculating the minimum value of waste heat. For the expected and the maximum calculations, the entries were adjusted in the normal manner using default values. Adjusting the data in this manner results in minimum waste heat totals which reflect the absolute minimum waste heat that can be based on the NEDS data.

An overall concern of this analysis was to avoid excluding any points from the file that could represent valid reports. Certain entries that remain in the file after the defaulting procedure may not be totally accurate, but they do lie within a feasible range. By evaluating the output from the file, certain general trends can be identified. These trends, presented below, may affect the waste heat totals.

### 2.2.3 Factors Affecting Waste Heat Estimates

Many factors can affect the accuracy and the validity of the waste heat estimates. First, the assumptions required to develop the methodology for the calculation can either lower or raise the results. In addition, since the data base was designed to calculate emissions and not waste heat, it can affect the inventory results. An understanding of these effects and the limitations of the study is crucial to properly evaluate the results.

The temperature data in the NEDS file has the most significant effect on the results. Since NEDS is an emissions data base, the flue gas temperature is recorded at the stack exit, not at the furnace exit where heat recovery devices are located and heat recovery potential is the greatest. Flue gas temperatures are lower at the stack exit for several reasons including heat loss from the flue gas piping to the ambient air through convection, heat loss in pollution control processing and equipment, the introduction of dilution air into the flue gas streams, and air that inadvertantly infiltrates the flue gas streams. All these factors reduce the flue gas temperature and affect the waste heat recovery potential in two ways: (1) by lowering the heat content, or (2) by changing the heat value. To illustrate the significance of the temperature drop between the furnace exit and the stack exit, consider a natural gas-fired glass melter where flue gases released from the regenerator chamber are usually between 1200 and 1500°F (650 and 820°C). However, almost 50 percent of the NEDS entries using this process report flue gas temperatures under 600°F (320°C). Figure 7 is a typical histogram for the temperature range in the NEDS file.

Heat losses due to convective effects and those due to pollution control processing actually lower the heat content of the flue gas. The temperature lowering effect of pollution control equipment is clear from examining the NEDS temperature histograms. For example, in aluminum reverberatory furnaces flue gas temperatures for furnaces without control equipment generally range between 1700 to 1800°F (930-980°C) and 600 to 700°F (320-370°C). Only 14 percent of these entries are below 200°F (93°C), while 65 percent of the entries with pollution control equipment reported flue gas temperatures below 200°F (see Figures 8 and 9 ). This is a significant difference as a result of pollution control devices.

Air enters the flue gas stream through both dilution and infiltration. Dilution air intentionally is added to cool the stream, while infiltration is inadvertant. However, both have the same effect. Air at 60°F (16°C) infiltrating the gas stream does not change the total heat content of the gas (referenced to 60°F), but it does reduce the temperature significantly. If any air infiltration occurs, both the heat content of the flue gas and its potential as a heat source will be diminished in the available heat inventory (reference at 300°F (149°C)). Air infiltration also affects the waste heat totals in another way due to a volume effect. Any air which enters the flue gas stream increases the volume of the gas, thus lowering the bulk temperature.

The original flue gas calculations were based on the assumption that air infiltration does not occur. However, since infiltration does take place and air has a lower specific heat than flue gas, then the original calculations will be higher than the actual conditions. The effect of air infiltration was recognized and accounted for in part by developing the enthalpy functions used to calculate waste heat. It is difficult to determine or even accurately estimate the amount of air infiltration in a given facility from NEDS data or even from the operators since they do not know the amount of infiltration that occurs. However, it is doubtful that air infiltration can affect the waste heat results by more than ten percent.

```
SCC = 39000608   Total Cases = 58   No Control Equipment SIC = 0

Temperature
  Range (°F)    Cases
                       ----------------------------------------------------------------------------------------------
    0-  60       0.    I
   61- 100       0.    I
  101- 200       0.    I
  201- 300       2.    H
  301- 400       5.    HH
  401- 500       8.    HHHH
  501- 600      12.    HHHHHH
  601- 700       4.    HH
  701- 800      15.    HHHHHHH
  801- 900       4.    HH
  901-1000       3.    H
 1001-1100       4.    HH
 1101-1200       1.    I
 1201-1300       0.    I
 1301-1400       0.    I
 1401-1500       0.    I
 1501-1600       0.    I
 1601-1700       0.    I
 1701-1800       0.    I
 1801-1900       0.    I
 1901-2000       0.    I
 2001-2100       0.    I
 2101-2200       0.    I
 2201-2300       0.    I
 2301-2400       0.    I
 2401-2500       0.    I
 2501-2600       0.    I
 2601-2700       0.    I
 2701-2800       0.    I
 2801-2900       0.    I
 2901-3000       0.    I
                       0--------20--------40--------60--------80--------100--------120--------140--------160--------180--------200
```

Note: $^{o}C = (^{o}F-32)/1.8$

Figure 7. NEDS flue gas temperature data for natural gas-fired glass melters.

```
SCC = 30400103   Total Cases = 188   No Control Equipment SIC = 0

Temperature
   Range(°F)     Cases
                          ------------------------------------------------------------------------------------------
    0-  60         0.     |
   61- 100        11.     |HHHHH
  101- 200        16.     |HHHHHHHH
  201- 300        16.     |HHHHHHHH
  301- 400        16.     |HHHHHHHH
  401- 500        12.     |HHHHHH
  501- 600        12.     |HHHHHH
  601- 700        25.     |HHHHHHHHHHHH
  701- 800         3.     |H
  801- 900         1.     |
  901-1000         6.     |HHH
 1001-1100         0.     |
 1101-1200         2.     |H
 1201-1300         8.     |HHHH
 1301-1400         2.     |H
 1401-1500        15.     |HHHHHHH
 1501-1600         0.     |
 1601-1700         0.     |
 1701-1800        38.     |HHHHHHHHHHHHHHHHHHH
 1801-1900         0.     |
 1901-2000         3.     |H
 2001-2100         0.     |
 2101-2200         0.     |
 2201-2300         2.     |H
 2301-2400         0.     |
 2401-2500         0.     |
 2501-2600         0.     |
 2601-2700         0.     |
 2701-2800         0.     |
 2801-2900         0.     |
 2901-3000         0.     |
                          0--------20--------40--------60--------80--------100--------120--------140--------160--------180--------200
```

Note: $^{o}C = (^{o}F-32)/1.8$

Figure 8. Aluminum reverberatory furnace.

```
SCC = 30400103   Total Cases = 110 with Control Equipment  SIC = 0

Temperature
   Range (°F)    Cases
                          ---------------------------------------------------------------------------------------------------------
   0-  60          5.    |HH
  61- 100         22.    |HHHHHHHHHHH
 101- 200         44.    |HHHHHHHHHHHHHHHHHHHHHH
 201- 300          7.    |HHH
 301- 400          5.    |HH
 401- 500          3.    |H
 501- 600          2.    |H
 601- 700          5.    |HH
 701- 800          2.    |H
 801- 900          1.    |
 901-1000          2.    |H
1001-1100          0.    |
1101-1200          1.    |
1201-1300          3.    |H
1301-1400          0.    |
1401-1500          3.    |H
1501-1600          1.    |
1601-1700          0.    |
1701-1800          0.    |
1801-1900          0.    |
1901-2000          1.    |
2001-2100          0.    |
2101-2200          2.    |H
2201-2300          0.    |
2301-2400          0.    |
2401-2500          1.    |
2501-2600          0.    |
2601-2700          0.    |
2701-2800          0.    |
2801-2900          0.    |
2901-3000          0.    |
                          0--------20--------40--------60--------80--------100--------120--------140--------160--------180--------200
```

__Note__:  $^{o}C = (^{o}F-32)/1.8$

Figure 9.   Aluminum reverberatory furnace.

The accuracy of the inventory also is affected by how complete the NEDS survey is. If plants are not included in the survey, the waste heat totals will be lower. For the most part, the coverage of NEDS is quite good, but in some SCC's there are a number of missing entries. For example, NEDS includes only about 90 metallurgical coke sources in the United States; this is far fewer than expected. The file also only reports 79 soaking pits in the U.S. while Battelle Laboratories reports over 2500 pits operating in 1975.[17] Part of this discrepancy can be attributed to the combination of several distinct operations into one source, but the bulk of the difference is probably due to the omission of installations from the file.

The waste heat totals could be on the high side if the stack flow entries that are blank in the file actually represent shutdown facilities. It would raise the waste heat totals in the expected and the maximum classifications since the stack flow data were adjusted from zero using the default procedure presented earlier, but would not affect the minimum totals since these entries remained zero for those calculations.

In industries where incineration of wastes is prevalent, the waste heat totals may appear to be high when compared with the reported energy consumption in the industry. However, these totals are actually valid. For example, since lumber mills burn wood waste, more energy exits from the stacks than would be expected from the fuel consumption of the manufacturing operations.

The available inventory is determined by calculating the energy contained in flue gases between the 300°F reference temperature and the point of release. Three hundred degrees is the theoretical lower limit from which heat can be transferred from the exiting flue gases. With current heat recovery devices, it is doubtful that this lower level will be reached for most non-boiler sources. The equipment would need to be very large and manufactured of expensive high grade materials. Therefore, the waste heat totals presented do not reflect the potential energy savings accurately. The amount of recoverable energy roughly can be estimated by the ratio of the temperature drop through the recovery device to the temperature drop relative to the reference temperature of 300°F.

## 2.3 RESULTS

The following section presents the results of the waste heat inventory analysis focusing on national totals, manufacturing group totals, temperature breakdowns, and several important SCC's. The full waste heat inventory results are presented in Volumes 2 to 10 of this report.

The waste heat inventory reports that approximately 14.1 quads (14.9 EJ) of energy are being released per year from all non-evaporative sources reported in the NEDS file. It also was calculated that 1.51 quads (1.59 EJ) of this heat are available, i.e., at temperatures higher than 300°F (149°C).

### 2.3.1 Temperature Histograms

The histograms developed in the preliminary part of the waste heat inventory are useful for assessing the flue gas heat potential from specific industrial processes. Many processes without pollution control equipment show bimodal distributions of exit temperatures (see Figure 8. ). Bimodality indicates facilities of the same type operate with and without heat recovery equipment. These processes may show the best potential for additional waste heat use in facilities not using recovery devices. The bimodal temperature distributions are not evident in the temperature reports from plants with pollution control equipment due to the equipment's temperature lowering effect (see Figure 9 ), but the potential for additional waste heat recovery may still exist. While the histograms reveal that the flue gas temperatures in these processes do not preclude heat recovery from being a viable option, they do not reveal the barriers which prevent adoption of heat recovery.

### 2.3.2 Inventory Description

The Source Code Classification (SCC) results are ordered numerically ranging from 1-01-001-01 to 3-99-999-99. Each SCC is divided into two groups: sources with and without pollution control equipment. If an SCC has entries in only one of the groups, i.e., with or without control equipment, then only that group is shown. The total SCC is presented in the same format.

The top left hand corner of each page of inventory output gives the SCC number and is followed immediately by a brief description of the SCC. A full listing of the SCC titles appears in Appendix H of this report. The file is organized such that SCC's beginning with 1 are boilers, 2 are internal combustion devices, and 3 are industrial processes, with 3.90 entries classified by process fuel. The top line indicates whether the information concerns entries with pollution control equipment, without equipment, or the total SCC.

The entry SIC = 0 indicates that the SCC has not been further subdivided by Standard Industrial Classification (SIC). However, if a four-digit number is given, the output includes the SCC entries also in the four-digit SIC. TOT RECS indicates the total number of records that were processed for the waste heat calculation for that section of the SCC. If SIC does not equal

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zero, TOT RECS will refer to the number of records in the total SCC, rather than the SIC subdivision of the SCC.

The first calculation results are given by temperature range. The flue gas heat content, given in Btu's, is entered in the appropriate one hundred degree range according to the flue gas exit temperature. The totals for the six different waste heat levels are given at the bottom of each column. The second page of the printout shows results tabulated by two-digit SIC's. The totals again appear at the bottom of each column. Finally, a histogram of the expected 60°F (16°C) waste heat calculation is shown. This histogram allows a more comprehensive analysis of the relative significance of the waste heat content of the various flue gases. Each "H" on the histograms represents $1 \times 10^{11}$ Btu's (105.5 TJ) and the exact heat value is given in the column directly to the left of the histograms. Any range with a heat value over ten trillion Btu's (10.6 PJ) will extend off the histogram scale and will not be reflected accurately.

Waste heat calculation results for the entire NEDS file are presented in the same format as an individual SCC with temperature and SIC breakdowns. The results are then divided into the two pollution control equipment categories. For certain broadly defined SCC's, the files have been further broken down by selected SIC and appear at the end of the inventory results (see Table 4).

### 2.3.3 Summary by SIC (two-digit)

The national waste heat inventory, divided by two-digit SIC's is presented in Tables 5, 6, and 7. By far the largest source of waste heat is in SIC 49, utilities. The waste heat total for utilities, 5.8 quads/year (6.1 EJ/yr), almost equals the combined waste heat of all manufacturing SIC's (20 to 39), which is 6.9 quads/year (7.3 EJ/yr).

Even though the waste heat total for utilities is quite large, the potential for recovery of the heat is not. The expected waste heat from the available heat inventory, 0.4 quads per year (0.4 EJ/yr), represents only seven precent of the total inventory for that SIC.

The manufacturing SIC's expected available inventory is 14 percent of the total inventory or 0.95 quads/year (1.00 EJ/yr), indicating a much better potential for flue gas heat recovery and use. Within the manufacturing sector, the best potential for the application of waste heat recovery lies in SIC 29 (refining) since 20 percent of the released heat is considered available. Other industrial groups which indicate better than average potential for waste heat recovery are SIC's 32, 33, and 34 (stone, clay, and glass manufacturing, primary metals, and fabricated metals, respectively). Good recovery potential is not only due to the high percentage of available heat, but also the large total value of the inventory. This comparison of heat potential is based on the assumption that the relative drop in flue gas temperature between the furnace exit and stack exit, the temperatures reported in NEDS, is approximately equal for all industries.

The waste heat results also were compared against energy consumption information from the Energy Consumption Data Base (ECDB)[27] in Table 8.

---

* This breakdown is found in the last half of Volume 10.

## TABLE 4. SIC BREAKDOWNS

| Standard Classification Code (SCC) | | Standard Industrial Code (SIC) | |
|---|---|---|---|
| 3-01-999-99 | Chemical Manufacturing - Other/ Not Classified | 2819 | Industrial Inorganic Chemicals, NEC* |
| | | 2821 | Plastic Materials, Synthetic Resins, and Nonvulcanizable Elastomers |
| | | 2834 | Pharmaceutical Preparations |
| | | 2869 | Industrial Organic Chemicals, NEC |
| 3-04-001-99 | Secondary Metals - Aluminum Operation - Other/Not Classified | 3334 | Primary Production of Aluminum |
| | | 3341 | Secondary Smelting and Refining of Nonferrous Metals |
| | | 3361 | Aluminum Foundries (Castings) |
| 3-04-999-99 | Secondary Metals - Other/ Not Classified | 3341 | Secondary Smelting and Refining of Nonferrous Metals |
| 3-05-014-01 | Mineral Products - Glass Manufacture - Soda-Lime General Furnace | 3211 | Flat Glass |
| | | 3221 | Glass Containers |
| | | 3229 | Presssed and Brown Glass and Glassware, NEC |
| 3-05-999-99 | Mineral Products - Other/ Not Classified | 2819 | Industrial Inorganic Chemicals, NEC |
| | | 2891 | Adhesives and Sealants |
| | | 3295 | Minerals and Earths, Ground or Otherwise Treated |
| 3-06-001-04 | Petroleum Industry - Process Heater - Gas | 1321 | Natural Gas Liquids |
| | | 2911 | Petroleum Refining |
| 3-90-005-05 | In-Process Fuel - Distillate Oil - Metal Melting | 3312 | Blast Furnaces (Including Coke Ovens), Steel Works, and Rolling Mills |
| | | 3341 | Secondary Smelting and Refining of Nonferrous Metals |
| 3-90-005-99 | In-Process Fuel - Distillate Oil - Other/Not Classified | 2816 | Inorganic Pigments |
| | | 2819 | Industrial Inorganic Chemicals, NEC |
| | | 2951 | Paving Mixtures and Blocks |
| | | 3295 | Minerals and Earths, Ground or Otherwise Treated |
| 3-90-006-05 | In-Process Fuel - Natural Gas - Metal Melting | 3312 | Blast Furnaces (Including Coke Ovens), Steel Works, and Rolling Mills |
| | | 3333 | Primary Smelting and Refining of Zinc |
| | | 3341 | Secondary Smelting and Refining of Nonferrous Metals |
| 3-90-006-99 | In-Process Fuel - Natural Gas - Other/Not Classified | 2819 | Industrial Inorganic Chemicals, NEC |
| | | 3221 | Glass Containers |
| | | 3295 | Minerals and Earths, Ground or Otherwise Treated |
| | | 3312 | Blast Furnaces (Including Coke Ovens), Steel Works, and Rolling Mills |
| 3-90-007-99 | In-Process Fuel - Process Gas - Other/Not Classified | 3312 | Blast Furnaces (Including Coke Ovens), Steel Works and Rolling Mills |
| 3-90-008-99 | In-Process Fuel - Coke - Other/Not Classified | 3321 | Gray Iron Foundries |

---

*NEC = Not Elsewhere Classified

## TABLE 5. WASTE HEAT INVENTORY RESULTS BY INDUSTRIAL GROUP
SUM--NO POLLUTION CONTROL EQUIPMENT--NUMBER OF RECORDS = 95,444*†

| | TOTAL | | | AVAILABLE | | |
|---|---|---|---|---|---|---|
| SIC | 60 MAXIMUM | 60 EXPECTED | 60 MINIMUM | 300 MAXIMUM | 300 EXPECTED | 300 MINIMUM |
| 1 | .130 E 13 | .103 E 13 | .862 E 11 | .107 E 12 | .102 E 12 | .113 E 11 |
| 2 | .237 E 13 | .188 E 13 | .456 E 12 | .131 E 12 | .125 E 12 | .206 E 11 |
| 3 | .832 E 12 | .640 E 12 | .349 E 12 | .126 E 11 | .120 E 11 | .104 E 11 |
| 6 | .127 E 11 | .992 E 10 | .577 E 10 | .945 E 09 | .897 E 09 | .821 E 09 |
| 7 | .443 E 13 | .389 E 13 | .292 E 12 | .949 E 11 | .901 E 11 | .103 E 11 |
| 8 | .269 E 12 | .212 E 12 | .313 E 11 | .262 E 11 | .249 E 11 | .700 E 10 |
| 9 | .340 E 11 | .275 E 11 | .223 E 10 | .754 E 10 | .718 E 10 | .236 E 09 |
| 10 | .373 E 14 | .294 E 14 | .959 E 13 | .244 E 13 | .231 E 13 | .702 E 12 |
| 12 | .629 E 13 | .545 E 13 | .418 E 12 | .310 E 12 | .295 E 12 | .369 E 11 |
| 13 | .221 E 15 | .180 E 15 | .169 E 14 | .520 E 14 | .494 E 14 | .618 E 13 |
| 14 | .375 E 14 | .316 E 14 | .429 E 13 | .191 E 13 | .181 E 13 | .427 E 12 |
| 15 | .325 E 12 | .253 E 12 | .116 E 12 | .207 E 11 | .197 E 11 | .154 E 11 |
| 16 | .565 E 13 | .469 E 13 | .117 E 11 | .191 E 13 | .181 E 13 | .406 E 10 |
| 17 | .911 E 12 | .732 E 12 | .761 E 11 | .251 E 11 | .239 E 11 | .920 E 10 |
| 19 | .125 E 14 | .991 E 13 | .334 E 13 | .155 E 13 | .147 E 13 | .969 E 12 |
| 20 | .323 E 15 | .258 E 15 | .530 E 14 | .235 E 14 | .223 E 14 | .938 E 13 |
| 21 | .913 E 13 | .724 E 13 | .333 E 13 | .109 E 13 | .103 E 13 | .795 E 12 |
| 22 | .133 E 15 | .106 E 15 | .365 E 14 | .120 E 14 | .114 E 14 | .631 E 13 |
| 23 | .782 E 13 | .613 E 13 | .108 E 13 | .585 E 12 | .555 E 12 | .135 E 12 |
| 24 | .252 E 15 | .202 E 15 | .359 E 14 | .267 E 14 | .254 E 14 | .456 E 13 |
| 25 | .289 E 14 | .229 E 14 | .451 E 13 | .269 E 13 | .256 E 13 | .967 E 12 |
| 26 | .311 E 15 | .243 E 15 | .995 E 14 | .210 E 14 | .200 E 14 | .133 E 14 |
| 27 | .119 E 14 | .927 E 13 | .305 E 13 | .678 E 12 | .644 E 12 | .227 E 12 |
| 28 | .747 E 15 | .594 E 15 | .220 E 15 | .793 E 14 | .753 E 14 | .339 E 14 |
| 29 | .760 E 15 | .614 E 15 | .218 E 15 | .148 E 15 | .141 E 15 | .795 E 14 |
| 30 | .589 E 14 | .473 E 14 | .149 E 14 | .517 E 13 | .491 E 13 | .795 E 14 |
| 31 | .693 E 13 | .550 E 13 | .197 E 13 | .937 E 12 | .890 E 12 | .591 E 12 |
| 32 | .428 E 15 | .351 E 15 | .106 E 15 | .873 E 14 | .829 E 14 | .294 E 14 |
| 33 | .151 E 16 | .125 E 16 | .589 E 15 | .285 E 15 | .271 E 15 | .183 E 15 |
| 34 | .131 E 15 | .107 E 15 | .247 E 14 | .239 E 14 | .226 E 14 | .922 E 13 |
| 35 | .637 E 14 | .510 E 14 | .153 E 14 | .669 E 13 | .630 E 13 | .228 E 13 |
| 36 | .585 E 14 | .473 E 14 | .175 E 14 | .491 E 13 | .467 E 13 | .214 E 13 |
| 37 | .107 E 15 | .849 E 14 | .256 E 14 | .927 E 13 | .881 E 13 | .348 E 13 |
| 38 | .146 E 14 | .122 E 14 | .540 E 13 | .107 E 13 | .102 E 13 | .392 E 12 |
| 39 | .245 E 14 | .195 E 14 | .510 E 13 | .253 E 13 | .240 E 13 | .992 E 12 |
| 40 | .950 E 13 | .734 E 13 | .284 E 13 | .430 E 12 | .408 E 12 | .137 E 12 |

TABLE 5. (continued).

| SIC | TOTAL<br>60 MAXIMUM | <br>60 EXPECTED | <br>60 MINIMUM | AVAILABLE<br>300 MAXIMUM | <br>300 EXPECTED | <br>300 MINIMUM |
|---|---|---|---|---|---|---|
| 41 | .303 E 12 | .236 E 12 | .179 E 11 | .207 E 11 | .197 E 11 | .194 E 09 |
| 42 | .303 E 13 | .244 E 13 | .301 E 12 | .117 E 12 | .111 E 12 | .531 E 11 |
| 43 | .687 E 12 | .535 E 12 | .127 E 11 | .462 E 11 | .439 E 11 | .0 |
| 44 | .300 E 13 | .247 E 13 | .123 E 12 | .388 E 12 | .370 E 12 | .237 E 11 |
| 45 | .393 E 13 | .304 E 13 | .897 E 12 | .173 E 12 | .164 E 12 | .108 E 12 |
| 46 | .193 E 14 | .159 E 14 | .160 E 12 | .569 E 13 | .541 E 13 | .591 E 11 |
| 47 | .305 E 12 | .242 E 12 | .690 E 11 | .366 E 11 | .347 E 11 | .226 E 11 |
| 48 | .176 E 12 | .139 E 12 | .160 E 11 | .218 E 11 | .207 E 11 | .478 E 09 |
| 49 | .288 E 16 | .227 E 16 | .983 E 15 | .334 E 15 | .318 E 15 | .174 E 15 |
| 50 | .611 E 13 | .512 E 13 | .533 E 12 | .481 E 12 | .457 E 12 | .119 E 12 |
| 51 | .130 E 15 | .112 E 15 | .201 E 13 | .974 E 13 | .925 E 13 | .464 E 12 |
| 52 | .140 E 13 | .112 E 13 | .463 E 10 | .210 E 12 | .199 E 12 | .717 E 08 |
| 53 | .264 E 13 | .207 E 13 | .468 E 12 | .170 E 12 | .161 E 12 | .877 E 11 |
| 54 | .123 E 13 | .943 E 12 | .181 E 11 | .632 E 11 | .600 E 11 | .172 E 10 |
| 55 | .186 E 12 | .150 E 12 | .135 E 11 | .965 E 10 | .916 E 10 | .161 E 09 |
| 56 | .181 E 11 | .140 E 11 | .0 | .665 E 09 | .631 E 09 | .0 |
| 57 | .209 E 12 | .162 E 12 | .0 | .103 E 11 | .978 E 10 | .0 |
| 58 | .214 E 12 | .168 E 12 | .271 E 10 | .207 E 11 | .197 E 11 | .563 E 09 |
| 59 | .714 E 12 | .553 E 12 | .110 E 12 | .315 E 11 | .299 E 11 | .173 E 11 |
| 60 | .668 E 12 | .520 E 12 | .121 E 12 | .407 E 11 | .387 E 11 | .133 E 11 |
| 63 | .689 E 12 | .535 E 12 | .293 E 12 | .395 E 11 | .375 E 11 | .336 E 11 |
| 64 | .618 E 11 | .489 E 11 | .297 E 11 | .828 E 10 | .786 E 10 | .719 E 10 |
| 65 | .204 E 14 | .158 E 14 | .323 E 13 | .114 E 13 | .108 E 13 | .417 E 12 |
| 66 | .911 E 11 | .687 E 11 | .478 E 10 | .204 E 09 | .193 E 09 | .177 E 09 |
| 67 | .868 E 10 | .657 E 10 | .0 | .0 | .0 | .0 |
| 70 | .405 E 13 | .314 E 13 | .410 E 12 | .255 E 12 | .242 E 12 | .598 E 11 |
| 71 | .342 E 10 | .320 E 10 | .261 E 10 | .0 | .0 | .0 |
| 72 | .473 E 13 | .369 E 12 | .482 E 12 | .339 E 12 | .332 E 12 | .821 E 11 |
| 73 | .894 E 13 | .734 E 13 | .370 E 13 | .259 E 13 | .346 E 13 | .191 E 13 |
| 75 | .737 E 12 | .604 E 12 | .522 E 11 | .292 E 11 | .277 E 11 | .392 E 10 |
| 76 | .398 E 12 | .317 E 12 | .255 E 11 | .294 E 11 | .279 E 11 | .0 |
| 77 | .190 E 11 | .148 E 11 | .0 | .665 E 09 | .631 E 09 | .0 |
| 78 | .693 E 11 | .537 E 11 | .957 E 09 | .277 E 10 | .263 E 10 | .258 E 09 |
| 79 | .840 E 12 | .667 E 12 | .112 E 11 | .125 E 12 | .119 E 12 | .217 E 10 |
| 80 | .922 E 14 | .720 E 14 | .186 E 14 | .719 E 13 | .682 E 13 | .320 E 13 |

TABLE 5. (continued).

| SIC | TOTAL<br>60 MAXIMUM | <br>60 EXPECTED | <br>60 MINIMUM | AVAILABLE<br>300 MAXIMUM | <br>300 EXPECTED | <br>300 MINIMUM |
|---|---|---|---|---|---|---|
| 82 | .140 E 15 | .110 E 15 | .267 E 14 | .117 E 14 | .112 E 14 | .495 E 13 |
| 83 | .399 E 13 | .311 E 13 | .190 E 12 | .290 E 12 | .275 E 12 | .150 E 11 |
| 84 | .329 E 11 | .255 E 11 | .102 E 11 | .144 E 10 | .137 E 10 | .943 E 09 |
| 86 | .135 E 13 | .106 E 13 | .163 E 12 | .117 E 12 | .111 E 12 | .306 E 11 |
| 88 | .504 E 11 | .392 E 11 | .0 | .280 E 10 | .265 E 10 | .0 |
| 89 | .410 E 13 | .321 E 13 | .105 E 13 | .284 E 12 | .269 E 12 | .158 E 12 |
| 90 | .498 E 12 | .392 E 12 | .234 E 12 | .553 E 11 | .525 E 11 | .481 E 11 |
| 91 | .409 E 14 | .319 E 14 | .833 E 13 | .290 E 13 | .275 E 13 | .943 E 12 |
| 92 | .124 E 14 | .968 E 13 | .155 E 13 | .112 E 13 | .107 E 13 | .290 E 12 |
| 93 | .389 E 13 | .308 E 13 | .519 E 12 | .517 E 12 | .491 E 12 | .940 E 11 |
| 94 | .239 E 12 | .189 E 12 | .154 E 10 | .310 E 11 | .295 E 11 | .270 E 09 |
| 95 | .215 E 12 | .168 E 12 | .245 E 11 | .183 E 11 | .174 E 11 | .741 E 10 |
| 96 | .565 E 13 | .446 E 13 | .139 E 13 | .680 E 12 | .646 E 12 | .500 E 12 |
| 97 | .571 E 14 | .449 E 14 | .866 E 13 | .558 E 13 | .530 E 13 | .172 E 13 |
| 99 | .257 E 15 | .205 E 15 | .429 E 14 | .333 E 14 | .317 E 14 | .963 E 13 |
| TOTAL SIC | .905 E 16 | .724 E 16 | .263 E 16 | .122 E 16 | .116 E 16 | .596 E 15 |

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*Note: 60°F = 16°C, 300°F = 149°C
†Energy given in Btu; 1 Btu = 1055J.

## TABLE 6. WASTE HEAT INVENTORY RESULTS BY INDUSTRIAL GROUP
## SUM--WITH POLLUTION CONTROL EQUIPMENT--NUMBER OF RECORDS = 58,507 *†

| | TOTAL | | | AVAILABLE | | |
|---|---|---|---|---|---|---|
| SIC | 60 MAXIMUM | 60 EXPECTED | 60 MINIMUM | 300 MAXIMUM | 300 EXPECTED | 300 MINIMUM |
| 1 | .234 E 12 | .188 E 12 | .100 E 12 | .260 E 11 | .247 E 11 | .226 E 11 |
| 2 | .417 E 12 | .352 E 12 | .593 E 11 | .115 E 12 | .110 E 12 | .227 E 09 |
| 4 | .577 E 10 | .541 E 10 | .0 | .0 | .0 | .0 |
| 5 | .132 E 14 | .101 E 14 | .553 E 13 | .0 | .0 | .0 |
| 7 | .771 E 13 | .711 E 13 | .192 E 13 | .185 E 09 | .176 E 09 | .161 E 09 |
| 8 | .621 E 10 | .551 E 10 | .411 E 10 | .0 | .0 | .0 |
| 10 | .495 E 14 | .387 E 14 | .157 E 14 | .415 E 12 | .395 E 12 | .135 E 12 |
| 11 | .105 E 12 | .785 E 11 | .398 E 11 | .0 | .0 | .0 |
| 12 | .225 E 14 | .191 E 14 | .611 E 13 | .682 E 12 | .647 E 12 | .508 E 12 |
| 13 | .451 E 13 | .361 E 13 | .533 E 11 | .800 E 12 | .760 E 12 | .180 E 11 |
| 14 | .501 E 14 | .408 E 14 | .149 E 14 | .798 E 12 | .758 E 12 | .675 E 12 |
| 15 | .965 E 11 | .732 E 11 | .656 E 09 | .0 | .0 | .0 |
| 16 | .952 E 12 | .750 E 12 | .133 E 12 | .634 E 11 | .604 E 11 | .644 E 09 |
| 17 | .329 E 11 | .274 E 11 | .508 E 10 | .0 | .0 | .0 |
| 19 | .544 E 12 | .425 E 12 | .102 E 11 | .294 E 11 | .279 E 11 | .0 |
| 20 | .222 E 15 | .180 E 15 | .534 E 14 | .849 E 13 | .806 E 13 | .529 E 13 |
| 21 | .852 E 13 | .670 E 13 | .306 E 13 | .324 E 12 | .308 E 12 | .234 E 12 |
| 22 | .452 E 14 | .356 E 14 | .188 E 14 | .264 E 13 | .251 E 13 | .213 E 13 |
| 23 | .998 E 12 | .795 E 12 | .143 E 12 | .877 E 11 | .833 E 11 | .450 E 11 |
| 24 | .102 E 15 | .820 E 14 | .329 E 14 | .761 E 13 | .722 E 13 | .482 E 13 |
| 25 | .251 E 14 | .206 E 14 | .695 E 13 | .241 E 13 | .229 E 13 | .126 E 13 |
| 26 | .559 E 15 | .432 E 15 | .222 E 15 | .240 E 14 | .227 E 14 | .196 E 14 |
| 27 | .102 E 13 | .855 E 12 | .583 E 12 | .133 E 12 | .127 E 12 | .115 E 12 |
| 28 | .378 E 15 | .301 E 15 | .144 E 15 | .213 E 14 | .202 E 14 | .151 E 14 |
| 29 | .263 E 15 | .209 E 15 | .871 E 14 | .303 E 14 | .286 E 14 | .227 E 14 |
| 30 | .278 E 14 | .223 E 14 | .120 E 14 | .246 E 13 | .233 E 13 | .206 E 13 |
| 31 | .575 E 12 | .464 E 12 | .246 E 12 | .233 E 11 | .221 E 11 | .202 E 11 |
| 32 | .778 E 15 | .614 E 15 | .259 E 15 | .569 E 14 | .539 E 14 | .403 E 14 |
| 33 | .101 E 16 | .803 E 15 | .355 E 15 | .919 E 14 | .873 E 14 | .552 E 14 |
| 34 | .309 E 14 | .253 E 14 | .121 E 14 | .208 E 13 | .198 E 13 | .141 E 13 |
| 35 | .234 E 14 | .189 E 14 | .710 E 13 | .148 E 13 | .140 E 13 | .844 E 12 |
| 36 | .204 E 14 | .167 E 14 | .936 E 13 | .152 E 13 | .145 E 13 | .132 E 13 |
| 37 | .778 E 14 | .618 E 14 | .303 E 14 | .558 E 13 | .530 E 13 | .457 E 13 |
| 38 | .126 E 14 | .982 E 13 | .541 E 13 | .424 E 12 | .403 E 12 | .355 E 12 |
| 39 | .724 E 14 | .552 E 14 | .284 E 14 | .118 E 13 | .112 E 13 | .828 E 12 |
| 40 | .143 E 13 | .118 E 13 | .159 E 12 | .801 E 11 | .760 E 11 | .118 E 11 |

TABLE 6. (continued).

| SIC | TOTAL<br>60 MAXIMUM | <br>60 EXPECTED | <br>60 MINIMUM | AVAILABLE<br>300 MAXIMUM | <br>300 EXPECTED | <br>300 MINIMUM |
|---|---|---|---|---|---|---|
| 41 | .369 E 11 | .346 E 11 | .352 E 10 | .0 | .0 | .0 |
| 42 | .578 E 12 | .533 E 12 | .869 E 11 | .0 | .0 | .0 |
| 43 | .309 E 11 | .243 E 11 | .0 | .348 E 10 | .331 E 10 | .0 |
| 44 | .182 E 14 | .142 E 14 | .780 E 13 | .136 E 13 | .129 E 13 | .111 E 13 |
| 45 | .217 E 12 | .176 E 12 | .114 E 12 | .487 E 11 | .463 E 11 | .423 E 11 |
| 46 | .452 E 12 | .345 E 12 | .436 E 11 | .158 E 11 | .150 E 11 | .0 |
| 47 | .449 E 12 | .350 E 12 | .195 E 12 | .158 E 11 | .150 E 11 | .137 E 11 |
| 48 | .363 E 10 | .283 E 10 | .165 E 10 | .270 E 09 | .256 E 09 | .234 E 09 |
| 49 | .456 E 16 | .350 E 16 | .177 E 16 | .881 E 14 | .836 E 14 | .702 E 14 |
| 50 | .746 E 13 | .653 E 13 | .237 E 13 | .842 E 12 | .800 E 12 | .729 E 12 |
| 51 | .333 E 14 | .298 E 14 | .405 E 13 | .101 E 13 | .956 E 12 | .862 E 12 |
| 52 | .452 E 11 | .424 E 11 | .631 E 10 | .0 | .0 | .0 |
| 53 | .201 E 11 | .151 E 11 | .742 E 10 | .0 | .0 | .0 |
| 55 | .537 E 10 | .500 E 10 | .404 E 10 | .0 | .0 | .0 |
| 57 | .345 E 10 | .293 E 10 | .202 E 10 | .0 | .0 | .0 |
| 59 | .247 E 11 | .232 E 11 | .113 E 11 | .0 | .0 | .0 |
| 62 | .272 E 12 | .209 E 12 | .115 E 12 | .227 E 10 | .263 E 10 | .241 E 10 |
| 65 | .963 E 12 | .738 E 12 | .405 E 12 | .582 E 09 | .553 E 09 | .506 E 09 |
| 70 | .273 E 11 | .217 E 11 | .133 E 11 | .415 E 10 | .349 E 10 | .360 E 10 |
| 72 | .168 E 13 | .138 E 13 | .533 E 12 | .227 E 11 | .216 E 11 | .177 E 10 |
| 73 | .275 E 12 | .234 E 12 | .291 E 11 | .111 E 10 | .106 E 10 | .941 E 09 |
| 75 | .171 E 12 | .148 E 12 | .352 E 11 | .755 E 08 | .717 E 08 | .656 E 08 |
| 76 | .103 E 12 | .842 E 11 | .113 E 10 | .232 E 11 | .221 E 11 | .583 E 08 |
| 80 | .134 E 14 | .105 E 14 | .402 E 13 | .994 E 12 | .944 E 12 | .690 E 12 |
| 82 | .496 E 14 | .389 E 14 | .180 E 14 | .439 E 13 | .417 E 13 | .311 E 13 |
| 83 | .117 E 13 | .942 E 12 | .100 E 12 | .256 E 12 | .243 E 12 | .270 E 11 |
| 84 | .199 E 09 | .187 E 09 | .152 E 09 | .0 | .0 | .0 |
| 89 | .946 E 12 | .742 E 12 | .436 E 12 | .953 E 11 | .905 E 11 | .828 E 11 |
| 90 | .217 E 11 | .172 E 11 | .106 E 11 | .330 E 10 | .313 E 10 | .286 E 10 |
| 91 | .627 E 13 | .492 E 13 | .573 E 12 | .566 E 12 | .537 E 12 | .190 E 12 |
| 92 | .466 E 13 | .362 E 13 | .462 E 12 | .267 E 12 | .253 E 12 | .973 E 11 |
| 93 | .184 E 14 | .142 E 14 | .705 E 13 | .123 E 12 | .116 E 12 | .753 E 11 |
| 95 | .278 E 11 | .235 E 11 | .132 E 11 | .506 E 08 | .480 E 08 | .440 E 08 |
| 96 | .388 E 12 | .299 E 12 | .853 E 11 | .127 E 11 | .121 E 11 | .0 |
| 97 | .198 E 14 | .154 E 14 | .729 E 13 | .136 E 13 | .129 E 13 | .894 E 12 |
| 99 | .245 E 15 | .191 E 15 | .833 E 14 | .750 E 13 | .712 E 13 | .447 E 13 |
| TOTAL SIC | .880 E 16 | .686 E 16 | .324 E 16 | .371 E 15 | .352 E 15 | .262 E 15 |

*Note: 60°F = 16°C, 300°F = 149°C †Energy given in Btu; 1 Btu = 1055J.

TABLE 7. WASTE HEAT INVENTORY RESULTS BY INDUSTRIAL GROUP
FINAL SUM--NUMBER OF RECORDS = 153,951*†

| | TOTAL | | | AVAILABLE | | |
|---|---|---|---|---|---|---|
| SIC | 60 MAXIMUM | 60 EXPECTED | 60 MINIMUM | 300 MAXIMUM | 300 EXPECTED | 300 MINIMUM |
| 1 | .154 E 13 | .121 E 13 | .186 E 12 | .133 E 12 | .126 E 12 | .339 E 11 |
| 2 | .279 E 13 | .224 E 13 | .515 E 12 | .247 E 12 | .234 E 12 | .208 E 11 |
| 3 | .832 E 12 | .640 E 12 | .349 E 12 | .126 E 11 | .120 E 11 | .104 E 11 |
| 4 | .577 E 10 | .541 E 10 | .0 | .0 | .0 | .0 |
| 5 | .132 E 14 | .101 E 14 | .553 E 13 | .0 | .0 | .0 |
| 6 | .127 E 11 | .992 E 10 | .557 E 10 | .945 E 09 | .897 E 09 | .821 E 09 |
| 7 | .121 E 14 | .110 E 14 | .221 E 13 | .951 E 11 | .903 E 11 | .105 E 11 |
| 8 | .276 E 12 | .217 E 12 | .354 E 11 | .262 E 11 | .249 E 11 | .700 E 10 |
| 9 | .340 E 11 | .275 E 11 | .223 E 10 | .754 E 10 | .718 E 10 | .236 E 09 |
| 10 | .868 E 14 | .681 E 14 | .253 E 14 | .286 E 13 | .271 E 13 | .837 E 12 |
| 11 | .105 E 12 | .785 E 11 | .398 E 11 | .0 | .0 | .0 |
| 12 | .288 E 14 | .246 E 14 | .653 E 13 | .992 E 12 | .942 E 12 | .545 E 12 |
| 13 | .226 E 15 | .183 E 15 | .170 E 14 | .528 E 14 | .502 E 14 | .620 E 13 |
| 14 | .876 E 14 | .723 E 14 | .192 E 14 | .271 E 13 | .257 E 13 | .110 E 13 |
| 15 | .421 E 12 | .326 E 12 | .117 E 12 | .207 E 11 | .197 E 11 | .154 E 11 |
| 16 | .660 E 13 | .544 E 13 | .144 E 12 | .197 E 13 | .187 E 13 | .471 E 10 |
| 17 | .943 E 12 | .759 E 12 | .811 E 11 | .251 E 11 | .239 E 11 | .920 E 10 |
| 19 | .131 E 14 | .103 E 14 | .335 E 13 | .158 E 13 | .150 E 13 | .969 E 12 |
| 20 | .545 E 15 | .438 E 15 | .106 E 15 | .319 E 14 | .303 E 14 | .147 E 14 |
| 21 | .176 E 14 | .139 E 14 | .639 E 13 | .141 E 13 | .134 E 14 | .103 E 13 |
| 22 | .178 E 15 | .141 E 15 | .553 E 14 | .147 E 14 | .139 E 14 | .844 E 13 |
| 23 | .882 E 13 | .693 E 13 | .123 E 13 | .672 E 12 | .639 E 12 | .180 E 12 |
| 24 | .354 E 15 | .284 E 15 | .688 E 14 | .343 E 14 | .326 E 14 | .938 E 13 |
| 25 | .540 E 14 | .435 E 14 | .115 E 14 | .510 E 13 | .485 E 13 | .223 E 13 |
| 26 | .870 E 15 | .675 E 15 | .322 E 15 | .450 E 14 | .427 E 14 | .330 E 14 |
| 27 | .129 E 14 | .101 E 14 | .363 E 13 | .811 E 12 | .771 E 12 | .343 E 12 |
| 28 | .113 E 16 | .895 E 15 | .364 E 15 | .101 E 15 | .955 E 14 | .550 E 14 |
| 29 | .102 E 16 | .823 E 15 | .305 E 15 | .178 E 15 | .170 E 15 | .102 E 15 |
| 30 | .867 E 14 | .697 E 14 | .269 E 14 | .763 E 13 | .724 E 13 | .396 E 13 |
| 31 | .751 E 13 | .596 E 13 | .221 E 13 | .960 E 12 | .912 E 12 | .611 E 12 |
| 32 | .121 E 16 | .965 E 15 | .365 E 15 | .144 E 15 | .137 E 15 | .697 E 14 |
| 33 | .252 E 16 | .205 E 16 | .944 E 15 | .377 E 15 | .358 E 16 | .238 E 15 |
| 34 | .162 E 15 | .132 E 15 | .368 E 14 | .260 E 14 | .246 E 14 | .106 E 14 |
| 35 | .871 E 14 | .699 E 14 | .224 E 14 | .817 E 13 | .770 E 13 | .312 E 13 |
| 36 | .789 E 14 | .640 E 14 | .269 E 14 | .643 E 13 | .612 E 13 | .346 E 13 |
| 37 | .185 E 15 | .147 E 15 | .559 E 14 | .149 E 14 | .141 E 14 | .805 E 13 |
| 38 | .272 E 14 | .220 E 14 | .108 E 14 | .150 E 13 | .142 E 13 | .747 E 12 |

TABLE 7. (continued).

| SIC | TOTAL<br>60 MAXIMUM | <br>60 EXPECTED | <br>60 MINIMUM | AVAILABLE<br>300 MAXIMUM | <br>300 EXPECTED | <br>300 MINIMUM |
|---|---|---|---|---|---|---|
| 39 | .969 E 14 | .747 E 14 | .335 E 14 | .371 E 13 | .352 E 13 | .175 E 13 |
| 40 | .109 E 14 | .852 E 13 | .300 E 13 | .510 E 12 | .484 E 12 | .149 E 12 |
| 41 | .340 E 12 | .270 E 12 | .214 E 11 | .207 E 11 | .197 E 11 | .194 E 09 |
| 42 | .361 E 13 | .297 E 13 | .388 E 12 | .117 E 12 | .111 E 12 | .531 E 11 |
| 43 | .718 E 12 | .560 E 12 | .127 E 11 | .497 E 11 | .472 E 11 | .0 |
| 44 | .212 E 14 | .167 E 14 | .792 E 13 | .174 E 13 | .166 E 13 | .113 E 13 |
| 45 | .415 E 13 | .321 E 13 | .101 E 13 | .221 E 12 | .210 E 12 | .150 E 12 |
| 46 | .198 E 14 | .162 E 14 | .204 E 12 | .571 E 13 | .543 E 13 | .591 E 11 |
| 47 | .754 E 12 | .592 E 12 | .264 E 12 | .524 E 11 | .498 E 11 | .363 E 11 |
| 48 | .179 E 12 | .142 E 12 | .177 E 11 | .221 E 11 | .210 E 11 | .713 E 09 |
| 49 | .745 E 16 | .577 E 16 | .276 E 16 | .422 E 15 | .402 E 15 | .245 E 15 |
| 50 | .136 E 14 | .117 E 14 | .290 E 13 | .132 E 13 | .126 E 13 | .848 E 12 |
| 51 | .163 E 15 | .142 E 15 | .606 E 13 | .108 E 14 | .102 E 14 | .133 E 13 |
| 52 | .145 E 13 | .116 E 13 | .109 E 11 | .210 E 12 | .199 E 12 | .717 E 08 |
| 53 | .266 E 13 | .209 E 13 | .475 E 12 | .170 E 12 | .161 E 12 | .877 E 11 |
| 54 | .123 E 13 | .943 E 12 | .181 E 11 | .632 E 11 | .600 E 11 | .172 E 10 |
| 55 | .192 E 12 | .155 E 12 | .175 E 11 | .965 E 10 | .916 E 10 | .616 E 09 |
| 56 | .181 E 11 | .140 E 11 | .0 | .665 E 09 | .631 E 09 | .0 |
| 57 | .213 E 12 | .165 E 12 | .202 E 10 | .103 E 11 | .978 E 10 | .0 |
| 58 | .214 E 12 | .168 E 12 | .271 E 10 | .207 E 11 | .197 E 11 | .563 E 09 |
| 59 | .739 E 12 | .576 E 12 | .121 E 12 | .315 E 11 | .229 E 11 | .173 E 11 |
| 60 | .668 E 12 | .520 E 12 | .121 E 12 | .407 E 11 | .387 E 11 | .133 E 11 |
| 62 | .272 E 12 | .209 E 12 | .115 E 12 | .277 E 10 | .263 E 10 | .241 E 10 |
| 63 | .689 E 12 | .535 E 12 | .293 E 12 | .395 E 11 | .375 E 11 | .336 E 11 |
| 64 | .618 E 11 | .489 E 11 | .279 E 11 | .828 E 10 | .786 E 10 | .719 E 10 |
| 65 | .213 E 14 | .166 E 14 | .364 E 13 | .114 E 13 | .108 E 13 | .418 E 12 |
| 66 | .911 E 11 | .687 E 11 | .478 E 10 | .204 E 09 | .193 E 09 | .177 E 09 |
| 67 | .868 E 10 | .657 E 10 | .0 | .0 | .0 | .0 |
| 70 | .408 E 13 | .317 E 13 | .424 E 12 | .259 E 12 | .246 E 12 | .634 E 11 |
| 71 | .342 E 10 | .320 E 10 | .261 E 10 | .0 | .0 | .0 |
| 72 | .641 E 13 | .507 E 13 | .102 E 13 | .362 E 12 | .344 E 12 | .838 E 11 |
| 73 | .922 E 13 | .757 E 13 | .373 E 13 | .259 E 13 | .246 E 13 | .191 E 13 |
| 75 | .908 E 12 | .752 E 12 | .874 E 11 | .293 E 11 | .278 E 11 | .398 E 10 |

TABLE 7. (continued).

| | TOTAL | | | AVAILABLE | | |
|---|---|---|---|---|---|---|
| SIC | 60 MAXIMUM | 60 EXPECTED | 60 MINIMUM | 300 MAXIMUM | 300 EXPECTED | 300 MINIMUM |
| 76 | .501 E 12 | .401 E 12 | .266 E 11 | .527 E 11 | .500 E 11 | .583 E 09 |
| 77 | .190 E 11 | .148 E 11 | .0 | .665 E 09 | .631 E 09 | .0 |
| 78 | .693 E 11 | .537 E 11 | .957 E 09 | .277 E 10 | .263 E 10 | .258 E 09 |
| 79 | .840 E 12 | .667 E 12 | .112 E 11 | .125 E 12 | .119 E 12 | .217 E 10 |
| 80 | .106 E 15 | .824 E 14 | .226 E 14 | .818 E 13 | .777 E 13 | .389 E 13 |
| 82 | .190 E 15 | .149 E 15 | .447 E 14 | .161 E 14 | .153 E 14 | .806 E 13 |
| 83 | .515 E 13 | .405 E 13 | .290 E 12 | .545 E 12 | .518 E 12 | .421 E 11 |
| 84 | .331 E 11 | .256 E 11 | .104 E 11 | .144 E 10 | .137 E 10 | .943 E 09 |
| 86 | .135 E 13 | .106 E 13 | .163 E 12 | .117 E 12 | .111 E 12 | .306 E 11 |
| 88 | .504 E 11 | .392 E 11 | .0 | .280 E 10 | .265 E 10 | .0 |
| 89 | .505 E 13 | .396 E 13 | .149 E 13 | .379 E 12 | .360 E 12 | .241 E 12 |
| 90 | .520 E 12 | .410 E 12 | .245 E 12 | .586 E 11 | .557 E 11 | .509 E 11 |
| 91 | .471 E 14 | .368 E 14 | .890 E 13 | .347 E 13 | .329 E 13 | .113 E 13 |
| 92 | .170 E 14 | .133 E 14 | .201 E 13 | .139 E 13 | .132 E 13 | .387 E 12 |
| 93 | .223 E 14 | .172 E 14 | .757 E 13 | .640 E 12 | .608 E 12 | .169 E 12 |
| 94 | .239 E 12 | .189 E 12 | .154 E 10 | .310 E 11 | .295 E 11 | .270 E 09 |
| 95 | .242 E 12 | .191 E 12 | .377 E 11 | .183 E 11 | .174 E 11 | .745 E 10 |
| 96 | .604 E 13 | .476 E 13 | .148 E 13 | .693 E 12 | .658 E 12 | .500 E 12 |
| 97 | .769 E 14 | .603 E 14 | .160 E 14 | .694 E 13 | .659 E 13 | .262 E 13 |
| 99 | .502 E 15 | .396 E 15 | .126 E 15 | .408 E 14 | .388 E 14 | .141 E 14 |
| TOTAL SIC | .178 E 17 | .141 E 17 | .587 E 06 | .160 E 16 | .151 E 16 | .859 E 15 |

*Note: 60°F = 16°C, 300°F = 149°C
†Energy given in Btu; 1 Btu = 1055J.

## TABLE 8. WASTE HEAT INVENTORY RESULTS AND ENERGY CONSUMPTION DATA -- MANUFACTURING DATA *†

| | TOTAL | AVAILABLE | | | | |
|---|---|---|---|---|---|---|
| SIC | 60 EXP. | 300 MAX. | 300 EXP. | 300 MIN. | % Available ** | ECDB |
| 20 | .435 E 15 | .319 E 14 | .303 E 14 | .147 E 14 | 6.97 | .774 E 15 |
| 21 | .139 E 14 | .141 E 13 | .134 E 13 | .103 E 13 | 9.64 | .225 E 14 |
| 22 | .141 E 15 | .147 E 14 | .139 E 14 | .844 E 13 | 9.86 | .207 E 15 |
| 23 | .693 E 13 | .672 E 12 | .639 E 12 | .180 E 12 | 9.22 | .316 E 14 |
| 24 | .284 E 15 | .343 E 14 | .326 E 14 | .938 E 13 | 11.5 | .189 E 15 |
| 25 | .434 E 14 | .510 E 13 | .485 E 13 | .223 E 13 | 11.2 | .432 E 14 |
| 26 | .675 E 15 | .450 E 14 | .427 E 14 | .330 E 14 | 6.33 | .209 E 16 |
| 27 | .101 E 14 | .811 E 12 | .771 E 12 | .343 E 12 | 7.63 | .508 E 14 |
| 28 | .895 E 15 | .101 E 15 | .955 E 14 | .550 E 14 | 10.7 | .237 E 16 |
| 29 | .823 E 15 | .178 E 15 | .170 E 15 | .102 E 15 | 20.7 | .294 E 16 |
| 30 | .697 E 14 | .763 E 13 | .724 E 13 | .396 E 13 | 10.4 | .185 E 15 |
| 31 | .596 E 13 | .960 E 12 | .912 E 12 | .611 E 12 | 15.3 | .164 E 14 |
| 32 | .965 E 15 | .144 E 15 | .137 E 15 | .697 E 14 | 14.2 | .112 E 16 |
| 33 | .205 E 16 | .377 E 15 | .358 E 15 | .238 E 15 | 17.5 | .290 E 16 |
| 34 | .132 E 15 | .260 E 14 | .246 E 14 | .106 E 14 | 18.6 | .308 E 15 |
| 35 | .699 E 14 | .817 E 13 | .770 E 13 | .312 E 13 | 11.0 | .260 E 15 |
| 36 | .640 E 14 | .643 E 13 | .612 E 13 | .346 E 13 | 9.56 | .155 E 15 |
| 37 | .147 E 15 | .149 E 14 | .141 E 14 | .805 E 13 | 9.59 | .269 E 15 |
| 38 | .220 E 14 | .150 E 13 | .142 E 13 | .747 E 12 | 6.45 | .337 E 14 |
| 39 | .747 E 14 | .371 E 13 | .352 E 13 | .175 E 13 | 4.17 | .348 E 14 |
| TOTAL (20-39) | 6.927 E 15 (49.5%) | 1.003 E 15 | 9.532 E 14 (6.81%) | 5.663 E 14 | 13.8 | .140 E 17 |
| 49 | .577 E 16 | .422 E 15 | .402 E 15 | .245 E 15 | 6.97 | |

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* Note: 60°C = 16°C; 300°F = 149°C
† Energy given in Btu; 1 Btu = 1055J

**percent of ECDB

According to the inventory results, fuel efficiencies are lowest in SIC's 22, 24, 25, 32, and 33. Overall, the total manufacturing heat inventory represents 49 percent (6.9 quads (7.3 EJ)) of the energy consumed in the manufacturing sector.* The available heat inventory accounted for seven percent or 0.95 quads (1.00 EJ) of the energy consumed in the pertinent industries.

The comparison of these two data bases can be misleading in certain industries, since ECDB only considers fossil fuels used in direct heat, steam generation, and electricity generated.** In some instances significant portions of the flue gas heat are not the result of fuel consumption accounted for in ECDB such as exothermic chemical reactions, in industries where the incineration of vaporized solvents is common, or in industries where waste materials are burned without using supplemental heat.

### 2.3.4 Summary by Temperature Range

The results of the temperature tabulations of the waste heat inventory are presented in Tables 9, 10, and 11. These totals represent all the data points in the NEDS file and are not divided in any way by industry or group. According to NedS, the total waste heat inventory values peak around 300 to 400°F (150-200°C) while the available waste heat inventory peaks in the 600 to 700°F (310-370°C) range. Though 600°F flue gas is not especially valuable for the recovery of usable energy with current heat recovery devices except boiler economizers, stack temperatures in this range often have furnace exit temperatures in the 1000 to 1500°F (540-820°C).† If this is the case, as is indicated by temperature data in several industries, significant amounts of energy from industrial flue gases could be feasilby recovered.

Tables 12 and 13 give the percentages for the total and available inventory found in each 100 degree fahrenheit (56 degree centegrade) temperature range. A cumulative total and percentage of how much heat is released above each temperature range also is reported. These totals indicate that 0.2 quads (0.2 EJ) of energy available in flue gases are released at temperatures over 1000°F (538°C).

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* The ECDB data is for 1974. Most NEDS data is probably also for 1974, but the dates when NEDS data were entered is not clear. An entry in NEDS indicates when a source's record was last updated, but that does not indicate whether the data used in this analysis was affected, nor does it indicate what year the data was collected. Therefore, the estimated fuel use and waste heat emitted may be for different years.

** The ECDB has data on fuels such as natural gas, fuel oil, coal, coke oven gas, blast furnance gas, and waste products in the pulp and paper industry.

† Some devices such as Organic Rankine Cycle electric power generation systems are designed to use temperatures in the 600°F range. They are just being marketed and are considered experimental by many people.

## TABLE 9 WASTE HEAT INVENTORY RESULTS BY TEMPERATURE RANGE TOTAL POLLUTION CONTROL EQUIPMENT--NUMBER OF RECORDS = 153,951*†

| | TOTAL | | | AVAILABLE | | |
|---|---|---|---|---|---|---|
| TEMP. RANGE °F | 60 MAXIMUM | 60 EXPECTED | 60 MINIMUM | 300 MAXIMUM | 300 EXPECTED | 300 MINIMUM |
| 0-100 | 6.87 E 14 | 6.44 E 14 | 2.22 E 14 | .0 | .0 | .0 |
| 100-200 | 1.46 E 15 | 1.15 E 15 | 4.13 E 14 | .0 | .0 | .0 |
| 200-300 | 4.91 E 15 | 3.75 E 15 | 1.71 E 15 | .0 | .0 | .0 |
| 300-400 | 4.96 E 15 | 3.83 E 15 | 1.59 E 15 | 1.97 E 14 | 1.86 E 14 | 1.12 E 14 |
| 400-500 | 2.12 E 15 | 1.66 E 15 | 6.43 E 14 | 2.50 E 14 | 2.34 E 14 | 1.42 E 14 |
| 500-600 | 1.00 E 15 | 8.07 E 14 | 3.42 E 14 | 2.02 E 14 | 1.92 E 14 | 1.17 E 14 |
| 600-700 | 9.59 E 14 | 7.83 E 14 | 3.14 E 14 | 2.54 E 14 | 2.41 E 14 | 1.32 E 14 |
| 700-800 | 6.44 E 14 | 5.32 E 14 | 2.04 E 14 | 2.04 E 14 | 1.94 E 14 | 1.00 E 14 |
| 800-900 | 4.42 E 14 | 3.68 E 14 | 1.57 E 14 | 1.61 E 14 | 1.53 E 14 | 8.50 E 13 |
| 900-1000 | 2.48 E 14 | 2.09 E 14 | 1.18 E 14 | 9.90 E 13 | 9.42 E 13 | 6.80 E 13 |
| 1000-1100 | 7.62 E 13 | 6.44 E 13 | 3.37 E 13 | 3.37 E 13 | 3.12 E 13 | 2.05 E 13 |
| 1100-1200 | 7.19 E 13 | 6.14 E 13 | 2.73 E 13 | 3.37 E 13 | 3.21 E 13 | 1.76 E 13 |
| 1200-1300 | 2.94 E 13 | 2.52 E 13 | 1.62 E 13 | 1.47 E 13 | 1.39 E 13 | 1.09 E 13 |
| 1300-1400 | 3.71 E 13 | 3.21 E 13 | 1.04 E 13 | 1.95 E 13 | 1.84 E 13 | 7.25 E 12 |
| 1400-1500 | 1.70 E 13 | 1.48 E 13 | 7.32 E 12 | 9.50 E 12 | 9.02 E 12 | 5.21 E 12 |
| 1500-1600 | 2.14 E 13 | 1.87 E 13 | 5.85 E 12 | 1.23 E 13 | 1.17 E 13 | 4.23 E 12 |
| 1600-1700 | 3.91 E 13 | 3.41 E 13 | 9.06 E 12 | 2.31 E 13 | 2.20 E 13 | 6.52 E 12 |
| 1700-1800 | 2.86 E 13 | 2.52 E 13 | 1.42 E 13 | 1.76 E 13 | 1.67 E 13 | 1.02 E 13 |
| 1800-1900 | 1.11 E 13 | 9.79 E 12 | 4.95 E 12 | 2.88 E 13 | 2.73 E 13 | 5.67 E 12 |
| 1900-2000 | 4.45 E 13 | 3.93 E 13 | 7.95 E 12 | 2.88 E 13 | 2.73 E 13 | 5.67 E 12 |
| 2000-2100 | 7.42 E 12 | 6.58 E 12 | 1.72 E 12 | 4.94 E 12 | 4.63 E 12 | 1.28 E 12 |
| 2100-2200 | 6.82 E 12 | 6.06 E 12 | 1.00 E 12 | 4.62 E 12 | 4.30 E 12 | 7.85 E 11 |
| 2200-2300 | 5.94 E 12 | 5.28 E 12 | 1.87 E 12 | 4.14 E 12 | 3.80 E 12 | 1.52 E 12 |
| 2300-2400 | 1.18 E 13 | 1.05 E 13 | 7.60 E 12 | 8.38 E 12 | 7.63 E 12 | 6.36 E 12 |
| 2400-2500 | 2.05 E 12 | 1.82 E 12 | 1.16 E 11 | 1.48 E 12 | 1.33 E 12 | 1.02 E 11 |
| 2500-2600 | 2.31 E 12 | 2.06 E 12 | .0 | 1.71 E 12 | 1.52 E 12 | .0 |
| 2600-2700 | 2.19 E 12 | 1.95 E 12 | 1.57 E 11 | 1.65 E 12 | 1.46 E 12 | 1.45 E 11 |
| 2700-2800 | 2.61 E 11 | 2.34 E 11 | 4.82 E 10 | 2.01 E 11 | 1.76 E 11 | 4.59 E 10 |
| 2800-2900 | 1.31 E 12 | 1.17 E 12 | 9.52 E 11 | 1.03 E 12 | 8.91 E 11 | 9.47 E 11 |
| 2900-3000 | 5.31 E 11 | 4.76 E 11 | 9.95 E 10 | 4.23 E 11 | 3.66 E 11 | 1.02 E 11 |
| TOTAL | 1.78 E 16 | 1.41 E 16 | 5.87 E 15 | 1.60 E 15 | 1.51 E 15 | 8.59 E 14 |

*Energy in Btu's. 1 Btu = 1055J
†°C = (°F-32)/1.8

## TABLE 10. WASTE HEAT INVENTORY RESULTS BY TEMPERATURE RANGE TOTAL NO POLLUTION CONTROL EQUIPMENT--NUMBER OF RECORDS = 95,444*†

|  | TOTAL |  |  | AVAILABLE |  |  |
|---|---|---|---|---|---|---|
| TEMP. RANGE °F | 60 MAXIMUM | 60 EXPECTED | 60 MINIMUM | 300 MAXIMUM | 300 EXPECTED | 300 MINIMUM |
| 0-100 | 3.98 E 14 | 3.73 E 14 | 1.24 E 14 | .0 | .0 | .0 |
| 100-200 | 4.99 E 14 | 3.98 E 14 | 1.20 E 14 | .0 | .0 | .0 |
| 200-300 | 1.49 E 15 | 1.13 E 15 | 4.61 E 14 | .0 | .0 | .0 |
| 300-400 | 2.25 E 15 | 1.74 E 15 | 5.91 E 14 | 0.106 E 14 | 9.99 E 13 | 4.73 E 13 |
| 400-500 | 1.39 E 15 | 1.09 E 15 | 3.49 E 14 | 1.64 E 14 | 1.55 E 14 | 7.71 E 13 |
| 500-600 | 6.47 E 14 | 5.21 E 14 | 1.95 E 14 | 1.32 E 14 | 1.25 E 14 | 6.73 E 13 |
| 600-700 | 8.85 E 14 | 7.22 E 14 | 2.78 E 14 | 2.34 E 14 | 2.22 E 14 | 1.16 E 14 |
| 700-800 | 5.00 E 14 | 4.13 E 14 | 1.24 E 14 | 1.58 E 14 | 1.51 E 14 | 6.09 E 13 |
| 800-900 | 4.29 E 14 | 3.58 E 14 | 1.51 E 14 | 1.57 E 14 | 1.48 E 14 | 8.20 E 13 |
| 900-1000 | 2.25 E 14 | 1.90 E 14 | 1.08 E 14 | 8.98 E 13 | 8.54 E 13 | 6.22 E 13 |
| 1000-1100 | 6.89 E 13 | 5.82 E 13 | 3.01 E 13 | 2.96 E 13 | 2.82 E 13 | 1.83 E 13 |
| 1100-1200 | 6.07 E 13 | 5.18 E 13 | 2.15 E 13 | 2.84 E 13 | 2.71 E 13 | 1.39 E 13 |
| 1200-1300 | 2.22 E 13 | 1.91 E 13 | 1.27 E 13 | 1.11 E 13 | 1.05 E 13 | 8.56 E 12 |
| 1300-1400 | 3.39 E 13 | 2.93 E 13 | 8.76 E 12 | 1.78 E 13 | 1.69 E 13 | 6.12 E 12 |
| 1400-1500 | 1.43 E 13 | 1.24 E 13 | 5.95 E 12 | 7.94 E 12 | 7.55 E 12 | 4.28 E 12 |
| 1500-1600 | 9.76 E 12 | 8.52 E 12 | 4.02 E 12 | 5.63 E 12 | 5.35 E 12 | 2.96 E 12 |
| 1600-1700 | 2.40 E 12 | 2.09 E 13 | 8.98 E 12 | 1.43 E 13 | 1.36 E 13 | 6.46 E 12 |
| 1700-1800 | 2.57 E 13 | 2.26 E 13 | 1.27 E 13 | 1.58 E 13 | 1.50 E 13 | 9.13 E 12 |
| 1800-1900 | 1.01 E 13 | 8.90 E 12 | 4.34 E 12 | 6.35 E 12 | 6.03 E 12 | 3.10 E 12 |
| 1900-2000 | 4.12 E 13 | 3.64 E 13 | 5.60 E 12 | 2.66 E 13 | 2.53 E 13 | 3.99 E 12 |
| 2000-2200 | 7.13 E 12 | 6.33 E 12 | 1.72 E 12 | 4.75 E 12 | 4.45 E 12 | 1.28 E 12 |
| 2100-2200 | 6.82 E 12 | 6.06 E 12 | 1.00 E 12 | 4.62 E 12 | 4.30 E 12 | 7.85 E 11 |
| 2200-2300 | 5.94 E 12 | 5.28 E 12 | 1.87 E 12 | 4.14 E 12 | 3.80 E 12 | 1.52 E 12 |
| 2300-2400 | 5.93 E 12 | 5.27 E 12 | 3.38 E 12 | 4.20 E 12 | 3.82 E 12 | 2.83 E 12 |
| 2400-2500 | 2.05 E 12 | 1.82 E 12 | 1.16 E 11 | 1.48 E 12 | 1.33 E 12 | 1.02 E 11 |
| 2500-2600 | 0.00 E 0 | .0 | .0 | .0 | .0 | .0 |
| 2600-2700 | 1.97 E 12 | 1.76 E 12 | .0 | 1.49 E 12 | 1.32 E 12 | 4.59 E 10 |
| 2700-2800 | 2.61 E 11 | 2.34 E 11 | 4.82 E 10 | 2.01 E 11 | 1.76 E 11 | .0 |
| 2800-2900 | .0 | .0 | .0 | .0 | .0 | .0 |
| 2900-3000 | 4.34 E 11 | 3.89 E 10 | 2.87 E 10 | 3.46 E 11 | 2.99 E 11 | 2.93 E 10 |
| TOTAL | 9.05 E 15 | 7.24 E 15 | 2.63 E 15 | 1.22 E 15 | 1.16 E 15 | 5.96 E 14 |

*Energy in Btu's. 1 Btu = 1055J
†°C = (°F-32)/1.8

## TABLE 11. WASTE HEAT INVENTORY RESULTS BY TEMPERATURE RANGE TOTAL WITH POLLUTION CONTROL EQUIPMENT--NUMBER OF RECORDS = 58,507*†

| TEMP. RANGE °F | TOTAL | | | AVAILABLE | | |
|---|---|---|---|---|---|---|
| | 60 MAXIMUM | 60 EXPECTED | 60 MINIMUM | 300 MAXIMUM | 300 EXPECTED | 300 MINIMUM |
| 0-100 | 2.98 E 14 | 2.71 E 14 | 9.74 E 13 | .0 | .0 | .0 |
| 100-200 | 9.59 E 14 | 7.49 E 14 | 2.93 E 14 | .0 | .0 | .0 |
| 200-300 | 3.43 E 15 | 2.61 E 15 | 1.25 E 15 | .0 | .0 | .0 |
| 300-400 | 2.71 E 15 | 2.09 E 15 | 1.00 E 15 | 9.12 E 13 | 8.65 E 13 | 6.49 E 13 |
| 400-500 | 7.27 E 14 | 5.73 E 14 | 2.95 E 14 | 8.68 E 13 | 8.24 E 13 | 6.45 E 13 |
| 500-600 | 3.57 E 14 | 2.86 E 14 | 1.48 E 14 | 7.06 E 13 | 6.71 E 13 | 4.95 E 13 |
| 600-700 | 7.39 E 13 | 6.04 E 13 | 3.62 E 13 | 1.96 E 13 | 1.86 E 13 | 1.55 E 13 |
| 700-800 | 1.44 E 14 | 1.19 E 14 | 8.00 E 13 | 4.60 E 13 | 4.38 E 13 | 3.94 E 12 |
| 800-900 | 1.25 E 13 | 1.04 E 13 | 5.51 E 12 | 4.53 E 12 | 4.32 E 12 | 2.96 E 12 |
| 900-1000 | 2.25 E 13 | 1.90 E 13 | 9.85 E 12 | 9.22 E 12 | 8.78 E 12 | 5.78 E 12 |
| 1000-1100 | 7.32 E 12 | 6.20 E 12 | 3.64 E 12 | 3.15 E 12 | 3.00 E 12 | 2.21 E 12 |
| 1100-1200 | 1.12 E 13 | 9.55 E 12 | 5.79 E 12 | 5.25 E 12 | 5.00 E 12 | 3.73 E 12 |
| 1200-1300 | 7.18 E 12 | 6.15 E 12 | 3.52 E 12 | 3.57 E 12 | 3.40 E 12 | 2.36 E 12 |
| 1300-1400 | 3.16 E 12 | 2.73 E 12 | 1.62 E 12 | 1.68 E 12 | 1.59 E 12 | 1.14 E 12 |
| 1400-1500 | 2.76 E 12 | 2.41 E 12 | 1.36 E 12 | 1.55 E 12 | 1.47 E 12 | 9.87 E 11 |
| 1500-1600 | 1.17 E 13 | 1.01 E 13 | 1.76 E 12 | 6.67 E 12 | 6.35 E 12 | 1.27 E 12 |
| 1600-1700 | 1.51 E 13 | 1.32 E 13 | 7.88 E 10 | 8.89 E 12 | 8.44 E 12 | 5.68 E 10 |
| 1700-1800 | 2.93 E 12 | 2.58 E 12 | 1.50 E 12 | 1.79 E 12 | 1.70 E 12 | 1.08 E 12 |
| 1800-1900 | 1.01 E 12 | 8.86 E 11 | 6.12 E 11 | 6.26 E 11 | 5.94 E 11 | 4.39 E 11 |
| 1900-2000 | 3.34 E 12 | 2.96 E 12 | 2.34 E 12 | 2.17 E 12 | 2.06 E 12 | 1.67 E 12 |
| 2000-2100 | 2.87 E 11 | 2.54 E 11 | .0 | 1.91 E 11 | 1.79 E 11 | .0 |
| 2100-2200 | .0 | .0 | .0 | .0 | .0 | .0 |
| 2200-2300 | .0 | .0 | .0 | .0 | .0 | .0 |
| 2300-2400 | 5.90 E 12 | 5.25 E 12 | 4.22 E 12 | 4.18 E 12 | 3.81 E 12 | 3.53 E 12 |
| 2400-2500 | .0 | .0 | .0 | .0 | .0 | .0 |
| 2500-2600 | 2.31 E 12 | 2.06 E 12 | .0 | 1.71 E 12 | 1.52 E 12 | .0 |
| 2600-2700 | 2.18 E 11 | 1.94 E 11 | 1.57 E 11 | 1.63 E 11 | 1.45 E 11 | 1.45 E 11 |
| 2700-2800 | .0 | .0 | .0 | .0 | .0 | .0 |
| 2800-2900 | 1.31 E 12 | 1.17 E 12 | 9.52 E 11 | 1.03 E 12 | 8.91 E 11 | 9.47 E 11 |
| 2900-3000 | 9.70 E 10 | 8.69 E 10 | 7.08 E 10 | 7.74 E 10 | 6.67 E 10 | 7.24 E 10 |
| TOTAL | 8.80 E 15 | 6.86 E 15 | 3.24 E 15 | 3.70 E 14 | 3.52 E 14 | 2.62 E 14 |

*Energy in Btu's. 1 Btu = 1055J

†°C = (°F-32)/1.8

## TABLE 12. CUMULATIVE TEMPERATURE TOTALS--TOTAL INVENTORY

| Temperature Range °F | Heat ● in Range | Percent of Total* | Cumulative Total ● | Percent of Total* |
|---|---|---|---|---|
| 2900-3000 | .476 E 12 | 3.38 E-3 | .476 E 12 | 3.38 E-3 |
| 2800-2900 | .117 E 13 | 8.30 E 3 | .165 E 13 | 1.17 E-2 |
| 2700-2800 | .234 E 12 | 1.66 E-3 | .188 E 13 | 1.33 E-2 |
| 2600-2700 | .195 E 13 | 1.39 E-2 | .383 E 13 | 2.72 E-2 |
| 2500-2600 | .206 E 13 | 1.46 E-2 | .589 E 13 | 4.18 E-2 |
| 2400-2500 | .183 E 13 | 1.30 E-2 | .772 E 13 | 5.48 E-2 |
| 2300-2400 | .105 E 14 | 7.46 E-2 | .182 E 14 | 1.29 E-1 |
| 2200-2300 | .529 E 13 | 3.75 E-2 | .235 E 14 | 1.67 E-1 |
| 2100-2200 | .606 E 13 | 4.30 E-2 | .296 E 14 | 2.10 E-1 |
| 2000-2100 | .658 E 13 | 4.67 E-2 | .362 E 14 | 2.57 E-1 |
| 1900-2000 | .393 E 14 | .279 | .755 E 14 | 5.36 E-1 |
| 1800-1900 | .979 E 13 | 6.94 E-2 | .853 E 14 | 6.05 E-1 |
| 1700-1800 | .252 E 14 | .179 | .110 E 15 | 7.81 E-1 |
| 1600-1700 | .341 E 14 | .242 | .145 E 15 | 1.03 |
| 1500-1600 | .187 E 14 | .132 | .163 E 15 | 1.16 |
| 1400-1500 | .148 E 14 | .105 | .178 E 15 | 1.26 |
| 1300-1400 | .321 E 14 | .228 | .210 E 15 | 1.49 |
| 1200-1300 | .252 E 14 | .179 | .235 E 15 | 1.67 |
| 1100-1200 | .614 E 14 | .436 | .297 E 15 | 2.11 |
| 1000-1100 | .644 E 14 | .457 | .361 E 15 | 2.56 |
| 900-1000 | .209 E 15 | 1.48 | .570 E 15 | 4.05 |
| 800-900 | .368 E 15 | 2.61 | .938 E 15 | 6.66 |
| 700-800 | .532 E 15 | 3.78 | .147 E 16 | 10.4 |
| 600-700 | .783 E 15 | 5.55 | .225 E 16 | 16.0 |
| 500-600 | .807 E 15 | 5.73 | .306 E 16 | 21.7 |
| 400-500 | .167 E 16 | 11.8 | .472 E 16 | 33.5 |
| 300-400 | .383 E 16 | 27.1 | .855 E 16 | 60.7 |
| 200-300 | .375 E 16 | 26.6 | .123 E 17 | 87.3 |
| 100-200 | .115 E 16 | 8.15 | .134 E 17 | 95.1 |
| 0-100 | .644 E 15 | 4.57 | .1409 E 17 | 100 |

TOTAL* = 1.409 E 16
● = Btu's per year

NOTE: The results are the expected waste heat referenced to 60°F (16°C).

NOTE: 1 Btu = 1055J
°C = (°F-32)/1.8

## TABLE 13. CUMULATIVE TEMPERATURE TOTALS--AVAILABLE INVENTORY

| Temperature Range °F | Heat ● in Range | Percent of Total* | Cumulative Total ● | Percent of Total* |
|---|---|---|---|---|
| 2900-3000 ● | .366 E 12 | 2.42 E-2 | .366 E 12 | 2.42 E-2 |
| 2800-2900 | .891 E 12 | 5.90 E-2 | .126 E 13 | 8.34 E2 |
| 2700-2800 | .176 E 12 | 1.17 E-2 | .143 E 13 | 9.47 E-2 |
| 2600-2700 | .149 E 13 | 9.74 E-2 | .290 E 13 | .192 |
| 2500-2600 | .152 E 13 | 0.101 | .442 E 13 | .293 |
| 2400-2500 | .133 E 13 | 8.81 E-2 | .575 E 13 | .381 |
| 2300-2400 | .763 E 13 | .505 | .134 E 14 | .887 |
| 2200-2300 | .380 E 13 | .252 | .172 E 14 | 1.14 |
| 2100-2200 | .430 E 13 | .285 | .215 E 14 | 1.42 |
| 2000-2100 | .463 E 13 | .307 | .261 E 14 | 1.73 |
| 1900-2000 | .273 E 14 | 1.81 | .535 E 14 | 3.54 |
| 1800-1900 | .662 E 13 | .438 | .601 E 14 | 3.98 |
| 1700-1800 | .167 E 14 | 1.11 | .768 E 14 | 5.09 |
| 1600-1700 | .220 E 14 | 1.46 | .988 E 14 | 6.54 |
| 1500-1600 | .117 E 14 | .775 | .110 E 15 | 7.28 |
| 1400-1500 | .903 E 13 | .598 | .120 E 15 | 7.95 |
| 1300-1400 | .184 E 14 | 1.22 | .138 E 15 | 9.14 |
| 1200-1300 | .139 E 14 | .921 | .152 E 15 | 10.1 |
| 1100-1200 | .321 E 14 | 2.17 | .184 E 15 | 12.2 |
| 1000-1100 | .312 E 14 | 2.07 | .215 E 15 | 14.2 |
| 900-1000 | .942 E 14 | 6.24 | .309 E 15 | 20.5 |
| 800-900 | .153 E 15 | 10.1 | .462 E 15 | 30.6 |
| 700-800 | .194 E 15 | 12.8 | .656 E 15 | 43.4 |
| 600-700 | .241 E 15 | 16.0 | .898 E 15 | 59.5 |
| 500-600 | .192 E 15 | 12.7 | .109 E 16 | 72.2 |
| 400-500 | .237 E 17 | 15.7 | .133 E 16 | 88.1 |
| 300-400 | .186 E 15 | 12.3 | .151 E 16 | 100 |

TOTAL = 1.51 E 15

● = Btus per year

NOTE: The results are the expected waste heat referenced to 300°F (149°C).

NOTE: °C = (°F-32)/1.8
1 Btu = 1055J

### 2.3.5 Individual SCC's

This section of the report examines the waste heat output of specific SCC's. These SCC's were examined because they show, or would be expected to show, high waste heat totals. They also serve as examples for some general trends in the inventory.

#### 2.3.5.1 SCC 3-03-003-01 Metallurgical Coke By-product Oven - General

Coke ovens show a strong bimodal distribution (see Table 14 and Figure 10. The available inventory has approximately three trillion Btu's ( 3 PJ) per year in the range of 1600 to 2000°F (870-1090°C). Though most by-product coke ovens have extensive regenerative heat recovery systems, not all of the flue gas heat available to some processes is utilized fully. A site-specific plant analysis would be necessary to identify the exact heat sources since there are many heat release points in a coke-making operation.

#### 2.3.5.2 SCC 3-03-009-03 Basic Oxygen Furnace - General

The basic oxygen furnace (BOF) also releases a large amount of high temperature waste heat with 4.9 trillion Btu's (5.2 PJ) per year above 800°F (430°C) in the available inventory (see Table 15 and Figure 11 ). The basic oxygen furnace does not consume any fuel except for a small amount used in the preheating of ladles and vessels. The heat is the result of the exothermic steel refining process. This clearly precludes the use of heat for preheating combustion air. yet some heat could be used to preheat the furnace scrap charge after a few process modifications. In most cases, the heat probably would be used outside the BOF shop if it were recovered.

#### 2.3.5.3 SCC 3-03-009-11 Finish/Soaking Pits

The available waste heat inventory calculates 1.2 trillion Btu's (1.3 PJ) per year above 1000°F (540°C) for soaking pits (see Table 16 and Figure 12). This indicates a very good potential for additional waste heat recovery. Many pits in the United States already have recovery equipment installed but more equipment could be added. This SCC is especially important considering that 1.2 trillion Btu's (1.3 PJ) were released from only 80 sources listed in NEDS which, as previously noted, are only a fraction of the nation's soaking pits.

#### 2.3.5.4 SCC 3-03-009-01 and 3-03-009-02 Steel - Open Hearth

Open hearth furnaces in the steel industry, both with and without oxygen lances, have an estimated 3.72 trillion Btu's (3.92 PJ) of the available heat inventory above 900°F (480°C) (see Tables 17 and 18 and Figures 13 and 14 ). Even though all open hearth furnaces of standard design are fitted with regenerative heat recovery chambers, inventory results show significant amounts of energy are still recoverable. In some facilities, waste heat boilers are used after the regenerator to recover additional heat; additional air preheat is not necessary. Because of their inefficiency and long batch time (ten hours), most open hearths are being phased out of operation and do not hold much, if any, real potential for increased use of waste heat.

TABLE 14. WASTE HEAT OUTPUT-METALLURGICAL COKE BY-PRODUCT OVEN-GENERAL*†

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```
SCC= 30300301--COKE METAL B GENERAL                 -TOTAL SCC -SIC =    0 -TOT RECS =     88

    TEMP        MAXIMUM    EXPECTED     MINIMUM     MAXIMUM     EXPECTED    MINIMUM
                60 DEG     60 DEG       60 DEG      300 DEG     300 DEG     300 DEG
   0.- 100.     .228E 12   .214E 12     .177E 11    .0          .0          .0
 101.- 200.     .171E 13   .129E 13     .848E 11    .0          .0          .0
 201.- 300.     .292E 13   .222E 13     .117E 13    .0          .0          .0
 301.- 400.     .466E 13   .362E 13     .716E 12    .291E 12    .276E 12    .892E 11
 401.- 500.     .557E 13   .440E 13     .507E 12    .669E 12    .635E 12    .131E 12
 501.- 600.     .542E 13   .477E 13     .122E 13    .123E 13    .117E 13    .453E 12
 601.- 700.     .130E 13   .106E 13     .698E 12    .336E 12    .319E 12    .292E 12
 701.- 800.     .317E 12   .261E 12     .177E 12    .971E 11    .924E 11    .844E 11
 801.- 900.     .0         .0           .0          .0          .0          .0
 901.-1000.     .225E 13   .190E 13     .0          .928E 12    .883E 12    .0
1001.-1100.     .0         .0           .0          .0          .0          .0
1101.-1200.     .0         .0           .0          .0          .0          .0
1201.-1300.     .0         .0           .0          .0          .0          .0
1301.-1400.     .0         .0           .0          .0          .0          .0
1401.-1500.     .0         .0           .0          .0          .0          .0
1501.-1600.     .0         .0           .0          .0          .0          .0
1601.-1700.     .107E 13   .933E 12     .0          .628E 12    .597E 12    .0
1701.-1800.     .219E 13   .192E 13     .151E 13    .135E 13    .128E 13    .109E 13
1801.-1900.     .574E 12   .505E 12     .398E 12    .354E 12    .338E 12    .286E 12
1901.-2000.     .124E 13   .110E 13     .0          .808E 12    .767E 12    .0
2001.-2100.     .0         .0           .0          .0          .0          .0
2101.-2200.     .0         .0           .0          .0          .0          .0
2201.-2300.     .0         .0           .0          .0          .0          .0
2301.-2400.     .0         .0           .0          .0          .0          .0
2401.-2500.     .0         .0           .0          .0          .0          .0
2501.-2600.     .0         .0           .0          .0          .0          .0
2601.-2700.     .0         .0           .0          .0          .0          .0
2701.-2800.     .0         .0           .0          .0          .0          .0
2801.-2900.     .0         .0           .0          .0          .0          .0
2901.-3000.     .0         .0           .0          .0          .0          .0

                .299E 14   .242E 14     .650E 13    .669E 13    .634E 13    .242E 13
```

*Temperature in °F (°C = (°F-32)/1.8)
†Energy in Btu (1 kJ = 0.948 Btu)

```
SCC = 30300301--COKE METAL BGENERAL                 -TOTAL SCC -TOT RECS =      88

SIC            MAXIMUM    EXPECTED   MINIMUM    MAXIMUM    EXPECTED   MINIMUM
               60 DEG     60 DEG     60 DEG     300 DEG    300 DEG    300 DEG
  12           ,619E 12   ,541E 12   ,420E 12   ,361E 12   ,343E 12   ,290E 12
  28           ,412E 12   ,324E 12   ,192E 12   ,515E 11   ,489E 11   ,446E 11
  29           ,442E 12   ,340E 12   ,0         ,646E 10   ,613E 10   ,0
  33           ,277E 14   ,223E 14   ,546E 13   ,607E 13   ,576E 13   ,191E 13
  99           ,799E 12   ,651E 12   ,428E 12   ,205E 12   ,195E 12   ,179E 12

               ,299E 14   ,242E 14   ,650E 13   ,669E 13   ,636E 13   ,242E 13
CC 30300301--COKE METAL B GENERAL                   --TOTAL SCC  -SIC =    0 -TOT RECS =      88

EMP RANGE    COUNT

                         ----------------------------------------------------------------------------------------------------
   0,- 100,   ,214E 12   IHH
 101,- 200,   ,129E 13   IHHHHHHHHHHHH
 201,- 300,   ,222E 13   IHHHHHHHHHHHHHHHHHHHHHH
 301,- 400,   ,362E 13   IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
 401,- 500,   ,440E 13   IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
 501,- 600,   ,477E 13   IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
 601,- 700,   ,106E 13   IHHHHHHHHHH
 701,- 800,   ,261E 12   IHH
 801,- 900,   ,0         I
 901,-1000,   ,190E 13   IHHHHHHHHHHHHHHHHHHH
1001,-1100,   ,0         I
1101,-1200,   ,0         I
1201,-1300,   ,0         I
1301,-1400,   ,0         I
1401,-1500,   ,0         I
1501,-1600,   ,0         I
1601,-1700,   ,933E 12   IHHHHHHHHH
1701,-1800,   ,192E 13   IHHHHHHHHHHHHHHHHHHH
1801,-1900,   ,505E 12   IHHHHH
1901,-2000,   ,110E 13   IHHHHHHHHHHH
2001,-2100,   ,0         I
2101,-2200,   ,0         I
2201,-2300,   ,0         I
2301,-2400,   ,0         I
2401,-2500,   ,0         I
2501,-2600,   ,0         I
2601,-2700,   ,0         I
2701,-2800,   ,0         I
2801,-2900,   ,0         I
2901,-3000,   ,0         I
                         0---------10--------20--------30--------40--------50--------60--------70--------80--------90-------100
TEMP OUTSIDE CURVES         50,0
TEMP OUTSIDE CURVES         50,0
TEMP OUTSIDE CURVES         50,0
TEMP OUTSIDE CURVES         50,0
TEMP OUTSIDE CURVES         50,0
TEMP OUTSIDE CURVES         50,0
```

Note: *Temperature in $^{o}$F ($^{o}$C = ($^{o}$F-32)/1.8)
†Energy in Btu (1 kJ = 0.948 Btu)

Figure 10. Waste heat output--metallurgical coke by-product oven--general.

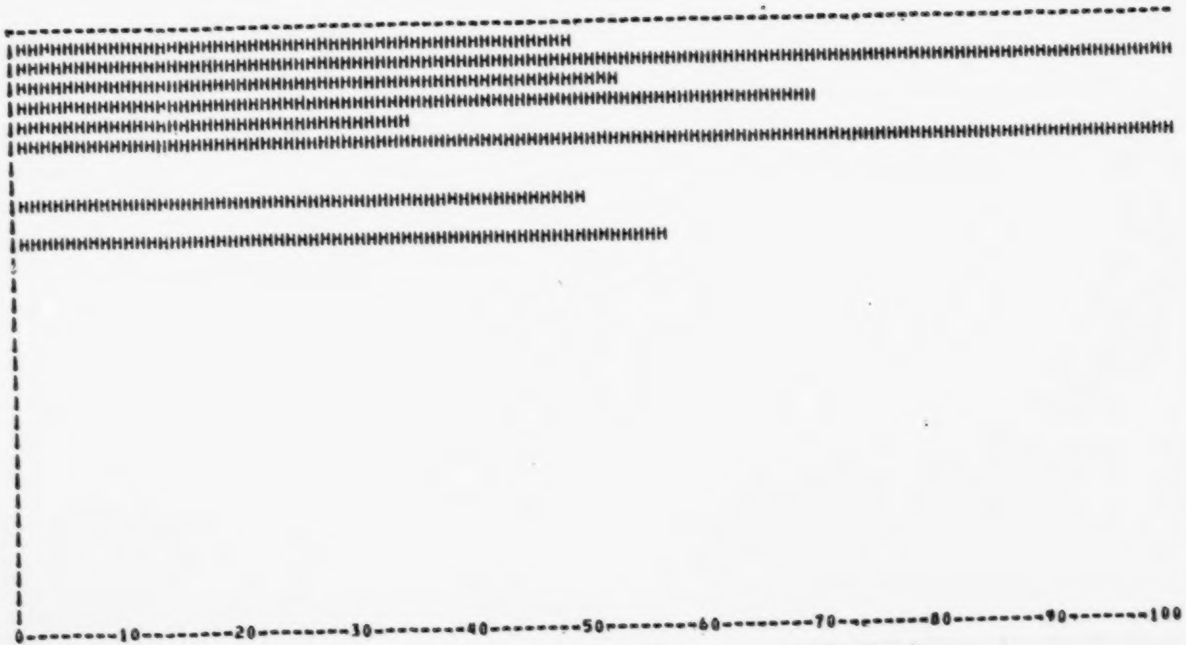
## TABLE 15. WASTE HEAT OUTPUT--BASIC OXYGEN FURNACE--GENERAL*†

SCC= 30300903--STEEL PROD BASIC OXYGEN FURNACE -TOTAL SCC -SIC =0 -TOT RECS =54

| TEMP | MAXIMUM 60 DEG | EXPECTED 60 DEG | MINIMUM 60 DEG | MAXIMUM 300 DEG | EXPECTED 300 DEG | MINIMUM 300 DEG |
|---|---|---|---|---|---|---|
| 0.- 100. | .512E 13 | .481E 13 | .392E 13 | .0 | .0 | .0 |
| 101.- 200. | .229E 14 | .182E 14 | .519E 13 | .0 | .0 | .0 |
| 201.- 300. | .699E 13 | .529E 13 | .278E 13 | .0 | .0 | .0 |
| 301.- 400. | .903E 13 | .699E 13 | .396E 13 | .368E 12 | .349E 12 | .320E 12 |
| 401.- 500. | .433E 13 | .344E 13 | .212E 13 | .658E 12 | .625E 12 | .572E 12 |
| 501.- 600. | .322E 14 | .258E 14 | .246E 13 | .618E 13 | .587E 13 | .811E 12 |
| 601.- 700. | .0 | .0 | .0 | .0 | .0 | .0 |
| 701.- 800. | .0 | .0 | .0 | .0 | .0 | .0 |
| 801.- 900. | .587E 13 | .492E 13 | .0 | .224E 13 | .213E 13 | .0 |
| 901.-1000. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1001.-1100. | .668E 13 | .567E 13 | .0 | .295E 13 | .280E 13 | .0 |
| 1101.-1200. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1201.-1300. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1301.-1400. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1401.-1500. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1501.-1600. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1601.-1700. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1701.-1800. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1801.-1900. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1901.-2000. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2001.-2100. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2101.-2200. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2201.-2300. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2301.-2400. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2401.-2500. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2501.-2600. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2601.-2700. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2701.-2800. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2801.-2900. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2901.-3000. | .0 | .0 | .0 | .0 | .0 | .0 |
|  | .931E 14 | .751E 14 | .204E 14 | .124E 14 | .118E 14 | .170E 13 |

Note: * Temperature in °F (°C = (°F-32)/1.8) † Energy in Btu (1 kJ = 0.948 Btu)

```
SCC = 30300903--STEEL PROD  BASIC OXYGEN FURNACE =TOTAL SCC =TOT RECS =     54

SIC          MAXIMUM    EXPECTED    MINIMUM    MAXIMUM   EXPECTED   MINIMUM
             60 DEG     60 DEG      60 DEG     300 DEG   300 DEG    300 DEG
  33        .931E 14   .751E 14    .204E 14   .124E 14  .118E 14   .170E 13


            .931E 14   .751E 14    .204E 14   .124E 14  .118E 14   .170E 13


CC 30300903--STEEL PROD   BASIC OXYGEN FURNACE--TOTAL SCC  =SIC =    0 =TOT RECS =     54

EMP RANGE   COUNT

   0.- 100.  .481E 13
 101.- 200.  .182E 14
 201.- 300.  .529E 13
 301.- 400.  .699E 13
 401.- 500.  .344E 13
 501.- 600.  .258E 14
 601.- 700.  .0
 701.- 800.  .0
 801.- 900.  .492E 13
 901.-1000.  .0
1001.-1100.  .567E 13
1101.-1200.  .0
1201.-1300.  .0
1301.-1400.  .0
1401.-1500.  .0
1501.-1600.  .0
1601.-1700.  .0
1701.-1800.  .0
1801.-1900.  .0
1901.-2000.  .0
2001.-2100.  .0
2101.-2200.  .0
2201.-2300.  .0
2301.-2400.  .0
2401.-2500.  .0
2501.-2600.  .0
2601.-2700.  .0
2701.-2800.  .0
2801.-2900.  .0
2901.-3000.  .0
```



Note: *Temperature in $^{o}$F ($^{o}$C = ($^{o}$F-32)/1.8)  -  †Energy in Btu (1 kJ = 0.948 Btu)

Figure 11.  Waste heat output--basic oxygen furnace--general.

## TABLE 16. WASTE HEAT OUTPUT--FINISH/SOAKING PITS*†

```
SCC= 30300911--STEEL PRO)   FINISHING AND SOAKIN -TOTAL SCC -SIC =    0 -TOT RECS =     80

   TEMP        MAXIMUM    EXPECTED    MINIMUM    MAXIMUM    EXPECTED   MINIMUM
               60 DEG     60 DEG      60 DEG     300 DEG    300 DEG    300 DEG
    0.- 100.   .229E 12   .215E 12   .0         .0         .0         .0
  101.- 200.   .193E 13   .144E 13   .529E 12   .0         .0         .0
  201.- 300.   .217E 12   .164E 12   .860E 11   .0         .0         .0
  301.- 400.   .262E 12   .204E 12   .119E 12   .194E 11   .185E 11   .169E 11
  401.- 500.   .279E 13   .222E 13   .102E 13   .424E 12   .402E 12   .275E 12
  501.- 600.   .941E 12   .762E 12   .494E 12   .219E 12   .208E 12   .191E 12
  601.- 700.   .451E 12   .369E 12   .246E 12   .127E 12   .120E 12   .110E 12
  701.- 800.   .166E 13   .138E 13   .444E 12   .550E 12   .524E 12   .224E 12
  801.- 900.   .122E 14   .101E 14   .594E 13   .419E 13   .399E 13   .308E 13
  901.-1000.   .151E 13   .127E 13   .302E 12   .615E 12   .586E 12   .174E 12
 1001.-1100.   .918E 12   .778E 12   .567E 12   .405E 12   .385E 12   .351E 12
 1101.-1200.   .135E 11   .115E 11   .850E 10   .635E 10   .604E 10   .550E 10
 1201.-1300.   .341E 12   .293E 12   .219E 12   .171E 12   .162E 12   .148E 12
 1301.-1400.   .0         .0         .0         .0         .0         .0
 1401.-1500.   .301E 12   .262E 12   .202E 12   .170E 12   .161E 12   .146E 12
 1501.-1600.   .0         .0         .0         .0         .0         .0
 1601.-1700.   .0         .0         .0         .0         .0         .0
 1701.-1800.   .853E 12   .750E 12   .590E 12   .529E 12   .498E 12   .424E 12
 1801.-1900.   .0         .0         .0         .0         .0         .0
 1901.-2000.   .0         .0         .0         .0         .0         .0
 2001.-2100.   .0         .0         .0         .0         .0         .0
 2101.-2200.   .0         .0         .0         .0         .0         .0
 2201.-2300.   .0         .0         .0         .0         .0         .0
 2301.-2400.   .0         .0         .0         .0         .0         .0
 2401.-2500.   .0         .0         .0         .0         .0         .0
 2501.-2600.   .0         .0         .0         .0         .0         .0
 2601.-2700.   .0         .0         .0         .0         .0         .0
 2701.-2800.   .0         .0         .0         .0         .0         .0
 2801.-2900.   .0         .0         .0         .0         .0         .0
 2901.-3000.   .0         .0         .0         .0         .0         .0

               .246E 14   .202E 14   .108E 14   .742E 13   .706E 13   .514E 13
```

Note: *Temperature in $^{o}F$ ($^{o}C = (^{o}F-32)/1.8$)
†Energy in Btu (1 kJ = 0.948 Btu)

```
        SIC         MAXIMUM      EXPECTED     MINIMUM       MAXIMUM      EXPECTED      MINIMUM
                   60 Degree    60 Degree    60 Degree    300 Degree   300 Degree   300 Degree

        33         .246E 14     .202E 14     .108E 14      .742E 13     .706E 13     .514E 13

                   .246E 14     .202E 14     .108E 14      .742E 13     .706E 13     .514E 13


SCC = 30300911   Total Cases = 80   SIC = 0

Temperature       Count
   Range
                             ----------------------------------------------------------------------------------------------------
   0- 100         .215E 12  |HH
 101- 200         .144E 13  |HHHHHHHHHHHHHH
 201- 300         .164E 12  |H
 301- 400         .204E 12  |HH
 401- 500         .222E 13  |HHHHHHHHHHHHHHHHHHHHHH
 501- 600         .762E 12  |HHHHHHH
 601- 700         .369E 12  |HHH
 701- 800         .138E 13  |HHHHHHHHHHHHH
 801- 900         .101E 14  |HHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
 901-1000         .127E 13  |HHHHHHHHHHHH
1001-1100         .778E 12  |HHHHHHH
1101-1200         .115E 11  |H
1201-1300         .293E 12  |HH
1301-1400         .0        |
1401-1500         .262E 12  |HH
1501-1600         .0        |
1601-1700         .0        |
1701-1800         .750E 12  |HHHHHHH
1801-1900         .0        |
1901-2000         .0        |
2001-2100         .0        |
2101-2200         .0        |
2201-2300         .0        |
2301-2400         .0        |
2401-2500         .0        |
2501-2600         .0        |
2601-2700         .0        |
2701-2800         .0        |
2801-2900         .0        |
2901-3000         .0        |
                            0--------10--------20--------30--------40--------50--------60--------70--------80--------90-------100
```

Note: *Temperature in $^{o}$F ($^{o}$C = ($^{o}$F-32)/1.8) - †Energy in Btu (1 kJ = 0.948 Btu)

Figure 12. Waste heat output--finish/soaking pits.

# TABLE 17. WASTE HEAT OUTPUT--STEEL--OPEN HEARTH*†

```
SCC= 30300901--STEEL PROD   OPEN HEARTH OXYGEN L =TOTAL SCC =SIC =    0 =TOT HECS =      87
   TEMP         MAXIMUM    EXPECTED    MINIMUM     MAXIMUM    EXPECTED    MINIMUM
                60 DEG     60 DEG      60 DEG      300 DEG    300 DEG     300 DEG
    0,- 100,    .118E 11   .110E 11    .0          .0         .0          .0
  101,- 200,    .437E 13   .326E 13    .160E 13    .0         .0          .0
  201,- 300,    .0         .0          .0          .0         .0          .0
  301,- 400,    .292E 14   .227E 14    .131E 14    .174E 13   .165E 13    .151E 13
  401,- 500,    .351E 14   .277E 14    .108E 14    .423E 13   .402E 13    .246E 13
  501,- 600,    .166E 14   .133E 14    .835E 13    .306E 13   .290E 13    .266E 13
  601,- 700,    .0         .0          .0          .0         .0          .0
  701,- 800,    .103E 14   .857E 13    .589E 13    .343E 13   .326E 13    .298E 13
  801,- 900,    .0         .0          .0          .0         .0          .0
  901,-1000,    .0         .0          .0          .0         .0          .0
 1001,-1100,    .525E 12   .446E 12    .324E 12    .232E 12   .221E 12    .201E 12
 1101,-1200,    .579E 12   .494E 12    .365E 12    .273E 12   .260E 12    .236E 12
 1201,-1300,    .220E 13   .195E 13    .146E 13    .114E 13   .108E 13    .986E 12
 1301,-1400,    .0         .0          .0          .0         .0          .0
 1401,-1500,    .0         .0          .0          .0         .0          .0
 1501,-1600,    .0         .0          .0          .0         .0          .0
 1601,-1700,    .0         .0          .0          .0         .0          .0
 1701,-1800,    .0         .0          .0          .0         .0          .0
 1801,-1900,    .0         .0          .0          .0         .0          .0
 1901,-2000,    .0         .0          .0          .0         .0          .0
 2001,-2100,    .0         .0          .0          .0         .0          .0
 2101,-2200,    .0         .0          .0          .0         .0          .0
 2201,-2300,    .0         .0          .0          .0         .0          .0
 2301,-2400,    .0         .0          .0          .0         .0          .0
 2401,-2500,    .0         .0          .0          .0         .0          .0
 2501,-2600,    .0         .0          .0          .0         .0          .0
 2601,-2700,    .0         .0          .0          .0         .0          .0
 2701,-2800,    .0         .0          .0          .0         .0          .0
 2801,-2900,    .0         .0          .0          .0         .0          .0
 2901,-3000,    .0         .0          .0          .0         .0          .0

                .990E 14   .784E 14    .419E 14    .141E 14   .134E 14    .110E 14
```

Note: *Temperature in $^{o}F$ ($^{o}C = (^{o}F-32)/1.8$)
†Energy in Btu (1 kJ = 0.948 Btu)

TABLE 18. WASTE HEAT OUTPUT--STEEL--OPEN HEARTHS*†

SCC= 30300902--STEEL PROD OPEN HEARTH NO OXYGE -TOTAL SCC -SIC = 0 -TOT RECS = 72

| TEMP | MAXIMUM 60 DEG | EXPECTED 60 DEG | MINIMUM 60 DEG | MAXIMUM 300 DEG | EXPECTED 300 DEG | MINIMUM 300 DEG |
|---|---|---|---|---|---|---|
| 0.- 100. | .0 | .0 | .0 | .0 | .0 | .0 |
| 101.- 200. | .204E 13 | .159E 13 | .796E 12 | .0 | .0 | .0 |
| 201.- 300. | .0 | .0 | .0 | .0 | .0 | .0 |
| 301.- 400. | .0 | .0 | .0 | .0 | .0 | .0 |
| 401.- 500. | .149E 14 | .118E 14 | .704E 13 | .168E 13 | .160E 13 | .146E 13 |
| 501.- 600. | .234E 12 | .188E 12 | .119E 12 | .450E 11 | .427E 11 | .391E 11 |
| 601.- 700. | .218E 12 | .178E 12 | .117E 12 | .564E 11 | .536E 11 | .490E 11 |
| 701.- 800. | .571E 13 | .471E 13 | .193E 13 | .179E 13 | .170E 13 | .910E 12 |
| 801.- 900. | .0 | .0 | .0 | .0 | .0 | .0 |
| 901.-1000. | .533E 13 | .449E 13 | .322E 13 | .219E 13 | .209E 13 | .190E 13 |
| 1001.-1100. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1101.-1200. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1201.-1300. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1301.-1400. | .143E 12 | .124E 12 | .931E 11 | .741E 11 | .704E 11 | .640E 11 |
| 1401.-1500. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1501.-1600. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1601.-1700. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1701.-1800. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1801.-1900. | .0 | .0 | .0 | .0 | .0 | .0 |
| 1901.-2000. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2001.-2100. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2101.-2200. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2201.-2300. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2301.-2400. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2401.-2500. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2501.-2600. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2601.-2700. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2701.-2800. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2801.-2900. | .0 | .0 | .0 | .0 | .0 | .0 |
| 2901.-3000. | .0 | .0 | .0 | .0 | .0 | .0 |
|  | .286E 14 | .231E 14 | .133E 14 | .584E 13 | .556E 13 | .443E 13 |

Note: *Temperature in °F (°C = (°F-32)/1.8) - †Energy in Btu (1 Kj = 0.948 Btu)

```
SCC = 30300901--STEEL PROD  OPEN HEARTH OXYGEN L -TOTAL SCC =TOT RECS =     87

SIC          MAXIMUM    EXPECTED    MINIMUM     MAXIMUM   EXPECTED    MINIMUM
             60 DEG     60 DEG      60 DEG     300 DEG    300 DEG    300 DEG
  33        .990E 14   .784E 14    .419E 14    .141E 14   .134E 14   .110E 14


            .990E 14   .784E 14    .419E 14    .141E 14   .134E 14   .110E 14


CC 30300901--STEEL PROD   OPEN HEARTH OXYGEN L--TOTAL SCC  =SIC =    0 =TOT RECS =     87

EMP RANGE   COUNT

                       *---------------------------------------------------------------------------------------------------*
    0,- 100,  .110E 11 IH
  101,- 200,  .326E 13 IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
  201,- 300,  .0       I
  301,- 400,  .227E 14 IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH 4HHH
  401,- 500,  .277E 14 IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH4HHH
  501,- 600,  .133E 14 IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH 4HHH
  601,- 700,  .0       I
  701,- 800,  .857E 13 IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
  801,- 900,  .0       I
  901,-1000,  .0       I
 1001,-1100,  .446E 12 IHHHH
 1101,-1200,  .494E 12 IHHHH
 1201,-1300,  .195E 13 IHHHHHHHHHHHHHHHHHHH
 1301,-1400,  .0       I
 1401,-1500,  .0       I
 1501,-1600,  .0       I
 1601,-1700,  .0       I
 1701,-1800,  .0       I
 1801,-1900,  .0       I
 1901,-2000,  .0       I
 2001,-2100,  .0       I
 2101,-2200,  .0       I
 2201,-2300,  .0       I
 2301,-2400,  .0       I
 2401,-2500,  .0       I
 2501,-2600,  .0       I
 2601,-2700,  .0       I
 2701,-2800,  .0       I
 2801,-2900,  .0       I
 2901,-3000,  .0       I
                       0--------10--------20--------30--------40--------50--------60--------70--------80--------90-------100
```

Note: *Temperature in $^{o}$F ($^{o}$C = ($^{o}$F-32)/1.8) - †Energy in Btu (1 kJ = 0.948 Btu)

Figure 13. Waste heat output--steel--open hearth.

```
SCC = 30300902--STEEL PROD  OPEN HEARTH NO OXYGE -TOTAL SCC -TOT RECS =      72
SIC          MAXIMUM    EXPECTED    MINIMUM    MAXIMUM   EXPECTED    MINIMUM
             60 DEG     60 DEG      60 DEG     300 DEG   300 DEG     300 DEG
   33        .286E 14   .231E 14    .133E 14   .584E 13  .556E 13    .443E 13

             .286E 14   .231E 14    .133E 14   .584E 13  .556E 13    .443E 13


CC 30300902--STEEL PROD   OPEN HEARTH NO OXYGE--TOTAL SCC  -SIC =   0 -TOT RECS =    72
EMP RANGE    COUNT
                    ----------------------------------------------------------------------------------------------------
   0.- 100.  .0         I
 101.- 200.  .159E 13   IHHHHHHHHHHHHH
 201.- 300.  .0         I
 301.- 400.  .0         I
 401.- 500.  .118E 14   IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
 501.- 600.  .188E 12   IH
 601.- 700.  .178E 12   IH
 701.- 800.  .471E 13   IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
 801.- 900.  .0         I
 901.-1000.  .449E 13   IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
1001.-1100.  .0         I
1101.-1200.  .0         I
1201.-1300.  .0         I
1301.-1400.  .124E 12   IH
1401.-1500.  .0         I
1501.-1600.  .0         I
1601.-1700.  .0         I
1701.-1800.  .0         I
1801.-1900.  .0         I
1901.-2000.  .0         I
2001.-2100.  .0         I
2101.-2200.  .0         I
2201.-2300.  .0         I
2301.-2400.  .0         I
2401.-2500.  .0         I
2501.-2600.  .0         I
2601.-2700.  .0         I
2701.-2800.  .0         I
2801.-2900.  .0         I
2901.-3000.  .0         I
                        0--------10--------20--------30--------40--------50--------60--------70--------80--------90-------100
```

Note: *Temperature in °F (°C = (°F-32)/1.8) - †Energy in Btu (1 kJ = 0.948 Btu)

Figure 14. Waste heat output--steel--open hearth.

### 2.3.5.5 SCC 3-04-001-03 Aluminum Reverberatory Furnace - Smelter

Aluminum reverberatory furnaces release 5.6 trillion Btu's (5.9 PJ) of heat above 1000°F (540°C) in the available inventory (see Table 19 ). The bimodal distribution of the released heat in this SCC is clear from the histogram of the total inventory (see Figure 15). The greater relative heating value of the flue gases released at higher temperatures can be seen by examining the temperature and flue gas heat histograms for the SCC's without control equipment (see Figures 8 and 16 ). The magnitude of the peak is around 1700°F (930°C) in the heat histogram and is much larger than the peak in the temperature histogram. Therefore, there is great potential for recovery in these furnaces.

### 2.3.5.6 SCC 3-05-006-04 Dry Cement, Gas-Fired Kilns

The waste heat totals for dry cement, gas-fired kilns are quite high, with 23 trillion Btu's (24 PJ) for the total inventory and 2.4 trillion (2.5 PJ) for the available inventory (see Table 20 and Figure 17 ). Since all of these SCC sources have pollution control equipment, flue gas exit temperatures are not over 600°F (320°C) which is too low for the economic recovery of energy for process heat. Due to the temperature lowering effect for the pollution control equipment, heat recovery potential is hidden. Since the typical flue gas temperature of cement kilns without a preheater is approximately 1100°F (590°C), the waste heat from these kilns is large enough to make it feasible to significantly increase waste heat recovery.

### 2.3.5.7 SCC 3-05-014-01 Glass Manufacturing, Soda Lime General Furnace

The available heat inventory reports 7.6 trillion Btu's (8.0 PJ) above 700°F (370°C) for glass manufacturing (see Table 21 and Figure 18 ). This high number is somewhat deceiving due to the high number of sources in the SCC. If all this energy could be recovered and recycled back into the process, an average 23.7 billion Btu's (25.0 TJ) per unit per year could be saved. If fuel can be purchased at the price of $2.50/MMBtu ($2.37/GJ), this would result in an average annual savings of about $60,000 per unit. However, given the efficiency of heat recovery devices, especially in this temperature range, and the fact that most glass furnaces already use preheated combustion air, the economics of waste heat recovery in this SCC may not be favorable.

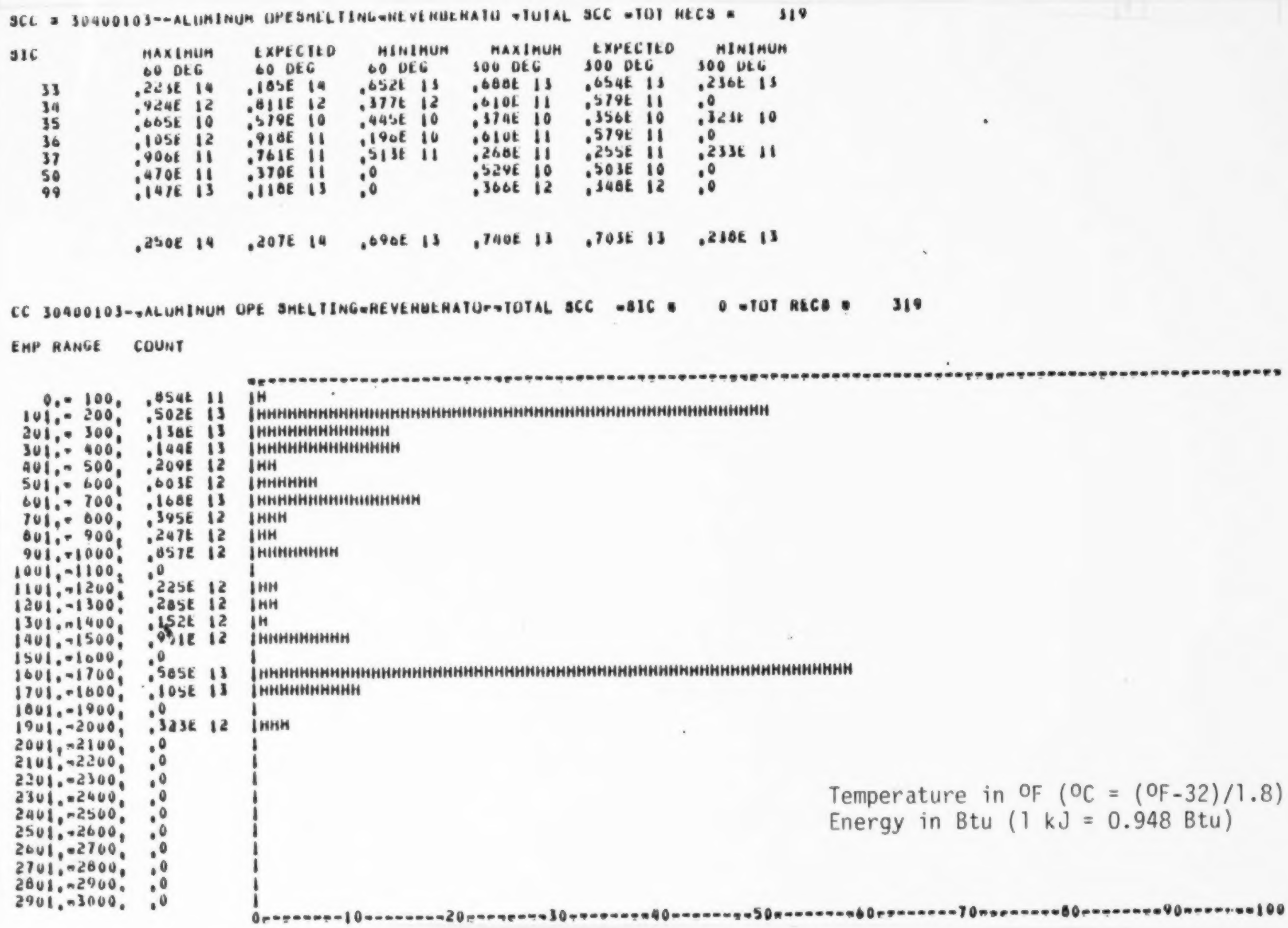
### 2.3.5.8 SCC 3-90-006-06 Natural Gas-Fired Brick Kilns

Of all SCC's, the waste heat from gas-fired brick kilns is the highest, with 5.95 trillion Btu's (6.30 PJ) released at a temperature over 1500°F (820°C) (see Table 22 and Figure 19 ). The clear bimodal distribution indicates that there are kilns releasing furnace exhaust directly to the atmosphere without heat recovery or other processing, thereby indicating the best potential for waste heat recovery use. However, the actual potential may be somewhat different. The minimum totals for most of the entries are zero, indicating that even though the sources report high stack temperatures, they do not report stack flow rates. For the minimum calculations, the flows

## TABLE 19. WASTE HEAT OUTPUT--ALUMINUM REVERBERATORY FURNACE--SMELTER*†

```
SCC= 30400103--ALUMINUM OPE SMELTING-REVERBERATO -TOTAL SCC =SIC =    6 =TOT RECS =    319

    TEMP        MAXIMUM    EXPECTED    MINIMUM     MAXIMUM    EXPECTED   MINIMUM
                60 DEG     60 DEG      60 DEG      300 DEG    300 DEG    300 DEG
    0.- 100.    .910E 11   .854E 11    .696E 11    .0         .0         .0
  101.- 200.    .628E 13   .502E 13    .138E 13    .0         .0         .0
  201.- 300.    .181E 13   .138E 13    .536E 12    .0         .0         .0
  301.- 400.    .187E 13   .144E 13    .786E 12    .478E 11   .453E 11   .386E 11
  401.- 500.    .265E 12   .209E 12    .821E 11    .334E 11   .318E 11   .199E 11
  501.- 600.    .745E 12   .603E 12    .389E 12    .169E 12   .161E 12   .147E 12
  601.- 700.    .205E 13   .168E 13    .108E 13    .555E 12   .528E 12   .471E 12
  701.- 800.    .478E 12   .395E 12    .269E 12    .152E 12   .144E 12   .132E 12
  801.- 900.    .295E 12   .247E 12    .175E 12    .113E 12   .107E 12   .979E 11
  901.-1000.    .102E 13   .857E 12    .527E 12    .409E 12   .389E 12   .305E 12
 1001.-1100.    .0         .0          .0          .0         .0         .0
 1101.-1200.    .261E 12   .225E 12    .165E 12    .123E 12   .117E 12   .106E 12
 1201.-1300.    .333E 12   .285E 12    .212E 12    .162E 12   .154E 12   .140E 12
 1301.-1400.    .176E 12   .152E 12    .0          .936E 11   .891E 11   .0
 1401.-1500.    .104E 13   .901E 12    .322E 12    .583E 12   .554E 12   .233E 12
 1501.-1600.    .0         .0          .0          .0         .0         .0
 1601.-1700.    .668E 13   .585E 13    .320E 11    .399E 13   .379E 13   .231E 11
 1701.-1800.    .119E 13   .105E 13    .677E 12    .733E 12   .696E 12   .486E 12
 1801.-1900.    .0         .0          .0          .0         .0         .0
 1901.-2000.    .364E 12   .323E 12    .258E 12    .237E 12   .225E 12   .104E 12
 2001.-2100.    .0         .0          .0          .0         .0         .0
 2101.-2200.    .0         .0          .0          .0         .0         .0
 2201.-2300.    .0         .0          .0          .0         .0         .0
 2301.-2400.    .0         .0          .0          .0         .0         .0
 2401.-2500.    .0         .0          .0          .0         .0         .0
 2501.-2600.    .0         .0          .0          .0         .0         .0
 2601.-2700.    .0         .0          .0          .0         .0         .0
 2701.-2800.    .0         .0          .0          .0         .0         .0
 2801.-2900.    .0         .0          .0          .0         .0         .0
 2901.-3000.    .0         .0          .0          .0         .0         .0

                .250E 14   .207E 14    .696E 13    .740E 13   .703E 13   .238E 13
```

*Temperature in °F (°C = (°F-32)/1.8)
†Energy in Btu (1 kJ = 0.948 Btu)



```
SCC = 30400103--ALUMINUM OPESMELTING=REVERBERATU =TOTAL SCC =TOT RECS =     319

SIC            MAXIMUM     EXPECTED     MINIMUM     MAXIMUM    EXPECTED    MINIMUM
               60 DEG      60 DEG       60 DEG      300 DEG    300 DEG     300 DEG
  33           ,223E 14    ,185E 14     ,652E 13    ,688E 13   ,654E 13    ,236E 13
  34           ,924E 12    ,811E 12     ,377E 12    ,610E 11   ,579E 11    ,0
  35           ,665E 10    ,579E 10     ,445E 10    ,374E 10   ,356E 10    ,323E 10
  36           ,105E 12    ,918E 11     ,196E 10    ,610E 11   ,579E 11    ,0
  37           ,906E 11    ,761E 11     ,513E 11    ,268E 11   ,255E 11    ,233E 11
  50           ,470E 11    ,370E 11     ,0          ,529E 10   ,503E 10    ,0
  99           ,147E 13    ,118E 13     ,0          ,366E 12   ,348E 12    ,0


               ,250E 14    ,207E 14     ,696E 13    ,740E 13   ,703E 13    ,238E 13


CC 30400103--ALUMINUM OPE SMELTING=REVERBERATU==TOTAL SCC  =SIC =    0 =TOT RECS =    319

EMP RANGE    COUNT

                       =-----------------------------------------------------------------------------------------------------
    0,- 100,   ,854E 11  |H
  101,- 200,   ,502E 13  |HHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
  201,- 300,   ,138E 13  |HHHHHHHHHHHHH
  301,- 400,   ,144E 13  |HHHHHHHHHHHHHH
  401,- 500,   ,209E 12  |HH
  501,- 600,   ,603E 12  |HHHHHH
  601,- 700,   ,168E 13  |HHHHHHHHHHHHHHHH
  701,- 800,   ,395E 12  |HHH
  801,- 900,   ,247E 12  |HH
  901,-1000,   ,857E 12  |HHHHHHHH
 1001,-1100,   ,0        |
 1101,-1200,   ,225E 12  |HH
 1201,-1300,   ,285E 12  |HH
 1301,-1400,   ,152E 12  |H
 1401,-1500,   ,951E 12  |HHHHHHHHH
 1501,-1600,   ,0        |
 1601,-1700,   ,585E 13  |HHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
 1701,-1800,   ,105E 13  |HHHHHHHHHH
 1801,-1900,   ,0        |
 1901,-2000,   ,323E 12  |HHH
 2001,-2100,   ,0        |
 2101,-2200,   ,0        |
 2201,-2300,   ,0        |
 2301,-2400,   ,0        |
 2401,-2500,   ,0        |
 2501,-2600,   ,0        |
 2601,-2700,   ,0        |
 2701,-2800,   ,0        |
 2801,-2900,   ,0        |
 2901,-3000,   ,0        |
                         0---------10--------20--------30--------40--------50--------60--------70--------80--------90--------100
```

Temperature in $^{0}$F ($^{0}$C = ($^{0}$F-32)/1.8)
Energy in Btu (1 kJ = 0.948 Btu)

Figure 15. Waste heat output--aluminum reverberatory furnace--smelter.

```
          SIC     MAXIMUM      EXPECTED     MINIMUM       MAXIMUM      EXPECTED     MINIMUM
                  60 Degree    60 Degree    60 Degree     300 Degree   300 Degree   300 Degree

          33     .133E 14     .113E 14     .349E 13      .614E 13     .583E 13     .172E 13
          34     .362E 12     .284E 12     .955E 11      .610E 11     .579E 11     .0
          35     .665E 10     .579E 10     .445E 10      .374E 10     .356E 10     .323E 10
          36     .105E 12     .918E 11     .196E 10      .610E 11     .579E 11     .0
          37     .809E 11     .670E 11     .461E 11      .268E 11     .255E 11     .233E 11
          50     .470E 11     .370E 11     .0            .529E 10     .503E 10     .0
          99     .612E 12     .537E 12     .0            .366E 12     .348E 12     .0

                 .145E 14     .124E 14     .364E 13      .666E 13     .632E 13     .174E 13

SCC = 30500604  Total Cases = 238 No Control Equipment  SIC = 0

Temperature   Count
  Range
                       I-----------------------------------------------------------------------------------------------------
   0- 100     .815E 11 IH
 101- 200     .461E 12 IHHHH
 201- 300     .175E 12 IH
 301- 400     .583E 12 IHHHHH
 401- 500     .164E 12 IH
 501- 600     .568E 12 IHHHHH
 601- 700     .706E 12 IHHHHHHH
 701- 800     .333E 12 IHHH
 801- 900     .165E 12 IH
 901-1000     .840E 12 IHHHHHHHH
1001-1100     .0       I
1101-1200     .166E 12 IH
1201-1300     .192E 12 IH
1301-1400     .152E 12 IH
1401-1500     .686E 12 IHHHHHH
1501-1600     .0       I
1601-1700     .585E 13 IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
1701-1800     .105E 13 IHHHHHHHHHH
1801-1900     .0       I
1901-2000     .195E 12 IH
2001-2100     .0       I
2101-2200     .0       I
2201-2300     .0       I
2301-2400     .0       I
2401-2500     .0       I
2501-2600     .0       I
2601-2700     .0       I                                                   Temperature in oF (oC = (oF-32)/1.8)
2701-2800     .0       I
2801-2900     .0       I                                                   Energy in Btu (1 kJ = 0.948 Btu)
2901-3000     .0       I
                       0--------10--------20--------30--------40--------50--------60--------70--------80--------90-------100
```

Figure 16. Waste heat output--aluminum reverberatory furnace - smelter.

## TABLE 20. WASTE HEAT OUTPUT--DRY CEMENT, GAS-FIRED KILNS*†

```
SCC= 30500604--CEMENT MANUF KILNS-GAS FIRED      -WITH CONTROL EQUIPMENT -SIC =    0 -TOT RECS =      66

   TEMP        MAXIMUM    EXPECTED    MINIMUM     MAXIMUM    EXPECTED    MINIMUM
                60 DEG     60 DEG      60 DEG     300 DEG    300 DEG     300 DEG
    0,- 100,  .210E 12   .197E 12   .258E 11   .0         .0          .0
  101,- 200,  .170E 13   .127E 13   .455E 12   .0         .0          .0
  201,- 300,  .374E 13   .285E 13   .108E 13   .0         .0          .0
  301,- 400,  .136E 14   .106E 14   .276E 13   .832E 12   .790E 12    .252E 12
  401,- 500,  .580E 13   .454E 13   .271E 13   .608E 12   .577E 12    .528E 12
  501,- 600,  .518E 13   .418E 13   .267E 13   .109E 13   .103E 13    .945E 12
  601,- 700,  .0         .0         .0         .0         .0          .0
  701,- 800,  .0         .0         .0         .0         .0          .0
  801,- 900,  .0         .0         .0         .0         .0          .0
  901,-1000,  .0         .0         .0         .0         .0          .0
 1001,-1100,  .0         .0         .0         .0         .0          .0
 1101,-1200,  .0         .0         .0         .0         .0          .0
 1201,-1300,  .0         .0         .0         .0         .0          .0
 1301,-1400,  .0         .0         .0         .0         .0          .0
 1401,-1500,  .0         .0         .0         .0         .0          .0
 1501,-1600,  .0         .0         .0         .0         .0          .0
 1601,-1700,  .0         .0         .0         .0         .0          .0
 1701,-1800,  .0         .0         .0         .0         .0          .0
 1801,-1900,  .0         .0         .0         .0         .0          .0
 1901,-2000,  .0         .0         .0         .0         .0          .0
 2001,-2100,  .0         .0         .0         .0         .0          .0
 2101,-2200,  .0         .0         .0         .0         .0          .0
 2201,-2300,  .0         .0         .0         .0         .0          .0
 2301,-2400,  .0         .0         .0         .0         .0          .0
 2401,-2500,  .0         .0         .0         .0         .0          .0
 2501,-2600,  .0         .0         .0         .0         .0          .0
 2601,-2700,  .0         .0         .0         .0         .0          .0
 2701,-2800,  .0         .0         .0         .0         .0          .0
 2801,-2900,  .0         .0         .0         .0         .0          .0
 2901,-3000,  .0         .0         .0         .0         .0          .0

              .302E 14   .236E 14   .970E 13   .253E 13   .240E 13    .173E 13
```

*Temperature in °F (°C = (°F-32)/1.8)
†Energy in Btu (1 kJ = 0.948 Btu)

```
SIC              MAXIMUM       EXPECTED       MINIMUM       MAXIMUM       EXPECTED       MINIMUM
                60 Degree     60 Degree      60 Degree    300 Degree    300 Degree     300 Degree

32              .290E 14      .227E 14       .937E 13      .247E 13      .235E 13      .168E 13
99              .121E 13      .929E 12       .338E 12      .576E 11      .547E 11      .501E 11

                .302E 14      .236E 14       .970E 13      .253E 13      .240E 13      .173E 13

SCC = 30500604  Total Cases = 66 with Control Equipment   SIC = 0

Temperature      Count
   Range                T----------------------------------------------------------------------------------------------------
   0- 100      .197E 12 IH
 101- 200      .127E 13 IHHHHHHHHHHHH
 201- 300      .285E 13 IHHHHHHHHHHHHHHHHHHHHHHHHHHH
 301- 400      .106E 14 IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
 401- 500      .456E 13 IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
 501- 600      .418E 13 IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
 601- 700      .0       I
 701- 800      .0       I
 801- 900      .0       I
 901-1000      .0       I
1001-1100      .0       I
1101-1200      .0       I
1201-1300      .0       I
1301-1400      .0       I
1401-1500      .0       I
1501-1600      .0       I
1601-1700      .0       I
1701-1800      .0       I
1801-1900      .0       I
1901-2000      .0       I
2001-2100      .0       I
2101-2200      .0       I
2201-2300      .0       I
2301-2400      .0       I
2401-2500      .0       I
2501-2600      .0       I
2601-2700      .0       I
2701-2800      .0       I
2801-2900      .0       I
2901-3000      .0       I
                        0--------10--------20--------30--------40--------50--------60--------70--------80--------90-------100
```

Temperature in $^{o}$F ($^{o}$C = ($^{o}$F-32)/1.8) - Energy in Btu (1 kJ = 0.948 Btu)

Figure 17. Waste heat output--dry cement, gas-fired kilns.

## TABLE 21. WASTE HEAT OUTPUT--GLASS MANUFACTURING, SODA LIME GENERAL FURNACE*†

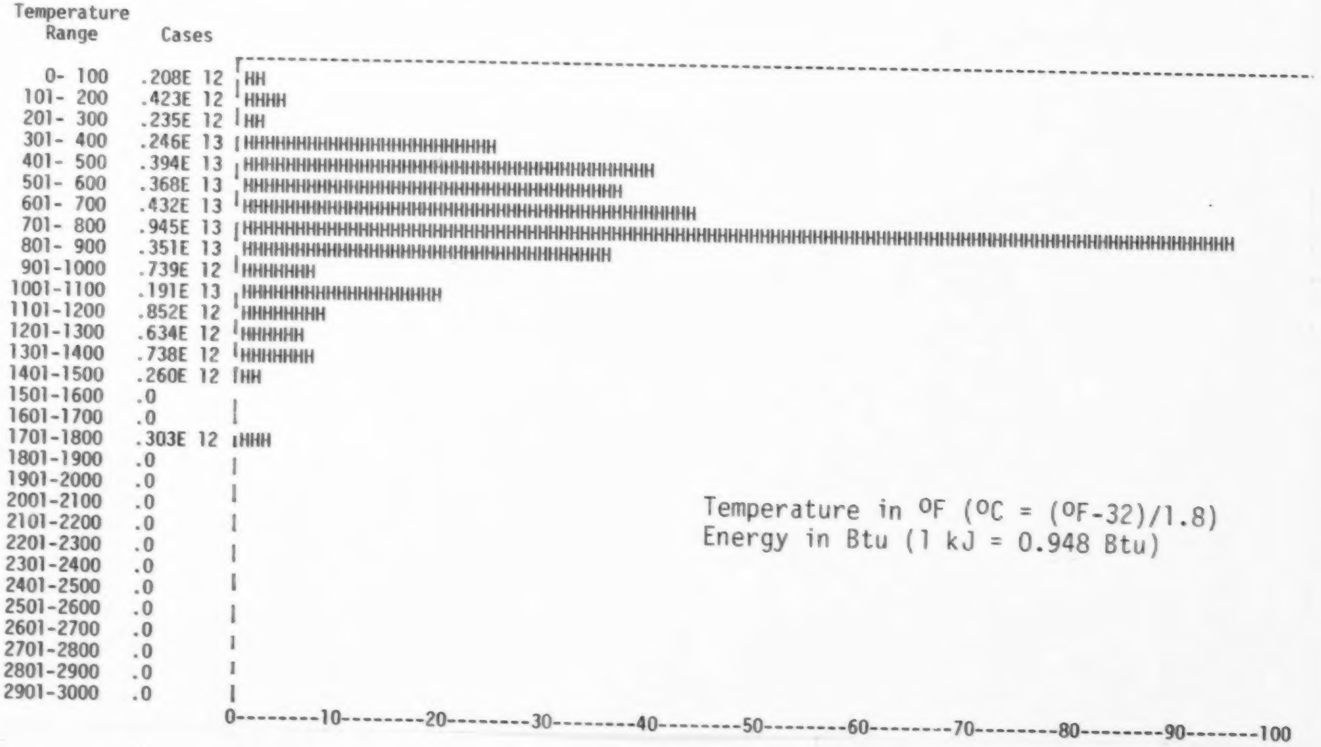
```
SCC= 30501401--GLASS MANUF  SODA-LIME GENERAL FU -TOTAL SCC -SIC =    0 -TOT RECS =    320

   TEMP         MAXIMUM    EXPECTED     MINIMUM     MAXIMUM     EXPECTED    MINIMUM
                60 DEG     60 DEG       60 DEG      300 DEG     300 DEG     300 DEG
    0.- 100.    .222E 12   .208E 12     .109E 12    .0          .0          .0
  101.- 200.    .567E 12   .423E 12     .208E 12    .0          .0          .0
  201.- 300.    .308E 12   .235E 12     .774E 11    .0          .0          .0
  301.- 400.    .316E 13   .246E 13     .905E 12    .171E 12    .163E 12    .963E 11
  401.- 500.    .499E 13   .394E 13     .199E 13    .602E 12    .572E 12    .431E 12
  501.- 600.    .456E 13   .368E 13     .183E 13    .100E 13    .949E 12    .661E 12
  601.- 700.    .529E 13   .432E 13     .276E 13    .142E 13    .135E 13    .119E 13
  701.- 800.    .115E 14   .945E 13     .256E 13    .357E 13    .340E 13    .125E 13
  801.- 900.    .420E 13   .351E 13     .171E 13    .155E 13    .148E 13    .927E 12
  901.-1000.    .880E 12   .739E 12     .526E 12    .346E 12    .330E 12    .301E 12
 1001.-1100.    .225E 13   .191E 13     .110E 13    .973E 12    .925E 12    .670E 12
 1101.-1200.    .998E 12   .852E 12     .306E 12    .468E 12    .445E 12    .196E 12
 1201.-1300.    .741E 12   .634E 12     .471E 12    .357E 12    .340E 12    .309E 12
 1301.-1400.    .854E 12   .738E 12     .0          .454E 12    .431E 12    .0
 1401.-1500.    .299E 12   .260E 12     .0          .168E 12    .160E 12    .0
 1501.-1600.    .0         .0           .0          .0          .0          .0
 1601.-1700.    .0         .0           .0          .0          .0          .0
 1701.-1800.    .345E 12   .303E 12     .0          .212E 12    .201E 12    .0
 1801.-1900.    .0         .0           .0          .0          .0          .0
 1901.-2000.    .0         .0           .0          .0          .0          .0
 2001.-2100.    .0         .0           .0          .0          .0          .0
 2101.-2200.    .0         .0           .0          .0          .0          .0
 2201.-2300.    .0         .0           .0          .0          .0          .0
 2301.-2400.    .0         .0           .0          .0          .0          .0
 2401.-2500.    .0         .0           .0          .0          .0          .0
 2501.-2600.    .0         .0           .0          .0          .0          .0
 2601.-2700.    .0         .0           .0          .0          .0          .0
 2701.-2800.    .0         .0           .0          .0          .0          .0
 2801.-2900.    .0         .0           .0          .0          .0          .0
 2901.-3000.    .0         .0           .0          .0          .0          .0

                .411E 14   .337E 14     .145E 14    .113E 14    .107E 14    .603E 13
```

*Temperature in $^{o}F$ ($^{o}C = (^{o}F-32)/1.8$)

†Energy in Btu (1 kJ = 0.948 Btu)

| SIC | MAXIMUM 60 Degree | EXPECTED 60 Degree | MINIMUM 60 Degree | MAXIMUM 300 Degree | EXPECTED 300 Degree | MINIMUM 300 Degree |
|---|---|---|---|---|---|---|
| 28 | .662E 11 | .548E 11 | .377E 11 | .219E 11 | .209E 11 | .191E 11 |
| 32 | .397E 14 | .324E 14 | .144E 14 | .108E 14 | .103E 14 | .594E 13 |
| 33 | .646E 11 | .541E 11 | .313E 11 | .247E 11 | .235E 11 | .215E 11 |
| 99 | .133E 13 | .110E 13 | .114E 12 | .448E 12 | .427E 12 | .543E 11 |
|  | .411E 14 | .337E 14 | .145E 14 | .113E 14 | .107E 14 | .603E 13 |

SCC = 30501401   Total Cases = 320   SCC = 0



Temperature in $^{o}$F ($^{o}$C = ($^{o}$F-32)/1.8)
Energy in Btu (1 kJ = 0.948 Btu)

Figure 18. Waste heat output--glass manufacturing.

## TABLE 22. WASTE HEAT OUTPUT--NATURAL GAS-FIRED BRICK KILNS*†

```
SCC= 39000606--NATURAL GAS  BRICK KILN AND DRY   =TOTAL SCC =SIC =    0 =TOT RECS =    206

   TEMP        MAXIMUM    EXPECTED     MINIMUM     MAXIMUM     EXPECTED    MINIMUM
               60 DEG     60 DEG      60 DEG      300 DEG     300 DEG     300 DEG
    0.- 100.   .120E 12   .112E 12    .628E 11    .0          .0          .0
  101.- 200.   .112E 13   .856E 12    .337E 12    .0          .0          .0
  201.- 300.   .275E 13   .210E 13    .446E 12    .0          .0          .0
  301.- 400.   .583E 13   .454E 13    .974E 12    .383E 12    .363E 12    .101E 12
  401.- 500.   .275E 13   .217E 13    .119E 13    .358E 12    .340E 12    .276E 12
  501.- 600.   .922E 12   .746E 12    .483E 12    .212E 12    .201E 12    .184E 12
  601.- 700.   .479E 12   .392E 12    .260E 12    .131E 12    .125E 12    .114E 12
  701.- 800.   .305E 12   .252E 12    .172E 12    .983E 11    .935E 11    .854E 11
  801.- 900.   .109E 12   .914E 11    .646E 11    .417E 11    .397E 11    .362E 11
  901.-1000.   .187E 12   .158E 12    .0          .772E 11    .734E 11    .0
 1001.-1100.   .0         .0          .0          .0          .0          .0
 1101.-1200.   .212E 12   .181E 12    .0          .997E 11    .948E 11    .0
 1201.-1300.   .0         .0          .0          .0          .0          .0
 1301.-1400.   .0         .0          .0          .0          .0          .0
 1401.-1500.   .0         .0          .0          .0          .0          .0
 1501.-1600.   .303E 10   .265E 10    .205E 10    .176E 10    .167E 10    .148E 10
 1601.-1700.   .272E 12   .239E 12    .0          .163E 12    .155E 12    .0
 1701.-1800.   .141E 13   .124E 13    .427E 10    .859E 12    .815E 12    .307E 10
 1801.-1900.   .175E 13   .154E 13    .0          .109E 13    .104E 13    .0
 1901.-2000.   .155E 13   .137E 13    .0          .101E 13    .954E 12    .0
 2001.-2100.   .176E 13   .156E 13    .0          .117E 13    .110E 13    .0
 2101.-2200.   .201E 13   .178E 13    .0          .136E 13    .127E 13    .0
 2201.-2300.   .706E 12   .628E 12    .0          .490E 12    .451E 12    .0
 2301.-2400.   .0         .0          .0          .0          .0          .0
 2401.-2500.   .387E 12   .345E 12    .0          .282E 12    .253E 12    .0
 2501.-2600.   .0         .0          .0          .0          .0          .0
 2601.-2700.   .0         .0          .0          .0          .0          .0
 2701.-2800.   .0         .0          .0          .0          .0          .0
 2801.-2900.   .0         .0          .0          .0          .0          .0
 2901.-3000.   .0         .0          .0          .0          .0          .0

               .246E 14   .205E 14    .399E 13    .782E 13    .736E 13    .802E 12
```

*Temperature in $^{o}F$ ($^{o}C = (^{o}F-32)/1.8$

†Energy in Btu (1 kJ = 0.948 Btu)

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```
SCC = 39000606--NATURAL GAS  BRICK KILN AND DRY  --  -NO CONTROL EQUIPMENT  =SIC=    0 =TOTAL RECS =    187

TEMP RANGE   COUNT
                         ----------------------------------------------------------------------------------------------
    0.- 100.  .111E 12  IH
  101.- 200.  .603E 12  IHHHHHH
  201.- 300.  .199E 13  IHHHHHHHHHHHHHHHHHHH
  301.- 400.  .450E 13  IHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHHH
  401.- 500.  .196E 13  IHHHHHHHHHHHHHHHHHHH
  501.- 600.  .746E 12  IHHHHHHH
  601.- 700.  .322E 12  IHHH
  701.- 800.  .252E 12  IHH
  801.- 900.  .914E 11  IH
  901.-1000.  .158E 12  IH
 1001.-1100.  .0        I
 1101.-1200.  .181E 12  IH
 1201.-1300.  .0        I
 1301.-1400.  .0        I
 1401.-1500.  .0        I
 1501.-1600.  .265E 10  IH
 1601.-1700.  .239E 12  IHH
 1701.-1800.  .124E 13  IHHHHHHHHHHHH
 1801.-1900.  .154E 13  IHHHHHHHHHHHHHHH
 1901.-2000.  .137E 13  IHHHHHHHHHHHHH
 2001.-2100.  .143E 13  IHHHHHHHHHHHHHH
 2101.-2200.  .178E 13  IHHHHHHHHHHHHHHHHH
 2201.-2300.  .628E 12  IHHHHHH
 2301.-2400.  .0        I
 2401.-2500.  .345E 12  IHHH
 2501.-2600.  .0        I
 2601.-2700.  .0        I
 2701.-2800.  .0        I
 2801.-2900.  .0        I
 2901.-3000.  .0        I
                        0---------10--------20--------30--------40--------50--------60--------70--------80--------90
```

Temperature in °F (°C = (°F-32)/1.8 - Energy in Btu (1 kJ = 0.948 Btu)

Figure 19. Waste heat output--natural gas-fired brick kiln.

remained zero; for the maximum and expected calculations, the mean flow rate would be defaulted. If the mean stack flow rate is not representative of the flow rates in the high temperature segment of the files, then the entries in this segment could be quite high. The kilns with high flue gas temperatures could be very small or low-use operations so they would not warrant the use of waste heat recovery or require pollution control. Regardless of whether the inventory accurately reflects the true waste heat potential of the process, brick kilns should be one of the first processes thoroughly investigated regarding the use of waste heat recovery.

### 2.3.6 Conclusion

In general, the inventory totals provide good general estimates concerning the waste heat released in the United States. The inventory reveals significant amounts of waste heat from many processes such as steel, aluminum, glass, cement, and chemical manufacture. It also reveals that, based on NEDS temperature data, most of the heat being released is of too low a quality to be usefully recycled in most processes. The inventory is especially valuable in assessing the relative potential of various SIC's. The temperature segmented inventory is distorted to some extent due to the effects of air infiltrating into the flue gases as well as pollution control equipment. But temperature based totals do serve in establishing a minimum for the quality of heat that will be encountered throughout an industry. The actual flue gas temperatures on which waste heat recovery technologies will be applied can be expected to be higher.

Even though problems exist with the baseline data from the NEDS file, most of the problems have been compensated for and they do not introduce any significant error into the inventory.

## 3. WASTE HEAT EQUIPMENT ANALYSIS

### 3.1 INTRODUCTION

The waste heat recovery equipment analysis determined the costs and applications of a variety of waste heat recovery equipment. The analysis examined five major equipment types and their limitations. Cost functions were developed using furnace flue gas flow rate and temperature, and air or water preheat temperature as inputs.

Table 23 lists the equipment types considered in the analysis. For all equipment, except waste heat boilers on direct-fired furnaces and recuperators on boilers, the potential for broad-based application was considered large enough to be analyzed for this project. Detailed descriptions are in the following sections.

Table 24 gives the sizes and temperature ranges of the heat recovery equipment. The equipment cost varies with the temperatures that the equipment must endure. Corrosion from both oxidation and sulfur attack can occur and special alloys are required to prolong equipment life.

Fuel savings is the only economic benefit of altered furnace performance which is considered. Increased furnace productivity can occur, but discussions with vendors indicated that generally it is not included in an economic evaluation of waste heat recovery equipment and is therefore not presented here as an economic savings.

Many types of energy conservation equipment were excluded from this analysis because site-specific factors which would have made their application more favorable than the common equipment types were not available in the Air Quality Control Region (AQCR) data base. Waste heat boilers have been excluded because most direct-fired industrial furnaces with the ability to use them are not in plants which require steam. Many times the only conceivable use of steam would be for space heating, but most industrial buildings containing furnaces are heated adequately by heat loss through furnace walls and openings. The steam quality produced may be too low for a plant's needs and some plants may require auxiliary firing.

Cogeneration systems, such as Organic Rankine Cycle Systems (ORCS), have been excluded because matching electricity demand to process heat needs, flue gas flow rate, and temperature was impractical for the large number of sources which exist in the AQCR's examined. Furthermore, the ORCS only would displace fuel at plants generating their own electricity. Because there are so few of these plants, the major emissions reduction would not occur in the AQCR, but rather, in the area surrounding the power plant formerly supplying the elec-

## TABLE 23. INDUSTRIAL FLUE GAS HEAT RECOVERY EQUIPMENT

| Heat Recovery Device | Furnace Type | | | |
|---|---|---|---|---|
| | Direct-Fired <980°C (1800°F) | Direct-Fired >980°C (1800°F) | Boilers | Tubestill Heaters |
| Recuperators | | | | |
| Radiation | Usually not used -- flue gas too cold. | Used. Do not need dilution air in co-current. | Not used. | Not used. |
| Convection | Metal construction. Do not need dilution air unless flue gas temperature is higher than design values. | Metal construction required dilution air. Ceramic used without dilution air. | Metallic units used, but much less frequently for high temperature applications. | Metallic units used, but product heating or waste heat boilers more common. |
| Regenerators | | | | |
| Checkerwork | Not used. | Retrofit on continuous units only when already have checker as primary heat recovery device. | Not used. | Not used. |
| Heat Wheel | Very compact. Metallic units sometimes used. Subject to fouling. | Very compact. Metallic or ceramic used. Subject to fouling. | Used, but economizers most common. | Used, but product heating or waste heat boilers more common. |
| Economizers | Not used. | Not used. | Commonly used and retrofitted. | Used to heat hydrocarbon product. |
| Waste Heat Boilers | Used where steam is required. Not much demand. | Used where steam is required. Not much demand. | Not used. | Used and retrofitted. |

## TABLE 24. TYPICAL FLUE GAS HEAT RECOVERY EQUIPMENT

| Furnace Type | Firing Rate, J/hr(MMBtu/hr) | Flue Gas Temp., °C(°F) | Air Preheat Temp., °C(°F) | Capital [2] Cost ($1000) | Theoretical Fuel Savings (%) |
|---|---|---|---|---|---|
| Recuperators (Furnaces) | | | | | |
| Convection: | | | | | |
| Batch Forge | 42.2 (40.0) | 820 (1500) | 540 (1000) | 110 | 25 |
| Batch Reheat | 57.5 (54.5) | 980 (1800) | 540 (1000) | 120 | 34 |
| Continuous Reheat | 262.7 (249.0) | 1090 (2000) | 430 (800) | 280 | 26 |
| Radiation: | | | | | |
| Batch Melt | 35.9 (34.0) | 1090 (2000) | 430 (800) | 143 | 26 |
| Reheat Forge, Soak | 33.4 (31.7) | 1200 (2200) | 430 (800) | 76 | 29 |
| Continuous | 19.4 (18.4) | 1390 (2500) | 670 (1250) | 201 | 46 |
| Preheaters (Tubestill Heaters) | | | | | |
| Air Preheat | 110.8 (105.0) | 440 (815) | 340 (650) | 1,000 | 16 |
| Steam Generation[3] | 2057[4]-3165 (1950-3000) | 540 (1000) | 370 (700) | 12,000 | variable[4] |
| Economizer (Boilers) | | Feedwater Outlet Temperature | | | |
| Oil/Gas-Fired Boiler | 184 (175) | 370 (700) | 170 (330) | 98.5 | 10.0 |
| Coal Fired Boiler | 343 (325) | 290 (550) | 140 (285) | 201.5 | 6.25 |
| Oil/Gas-Fired Boiler | 95 (90) | 320 (600) | 150 (300) | 52 | 7.5 |

---

[1] Firing Rate is before recuperation.

[2] Cost is in 1978 dollars and is the installed equipment cost.

[3] A 15,890 $m^3$/day (100,000 bbl/day) refinery, with 20 furnaces exhausted through a steam generating waste heat boiler into a common stock.

[4] Depending upon the magnitude of heat recovery supplied with the furnaces.

[5] Steam at 4.48 MPa (650 psig).

[6] Assuming inlet temperature to be 100°C and outlet temperature of flue gas to be 149°C.

tricity displaced by the OrCS. Therefore, in most applications, ORCS would save energy but not improve ambient air quality.

## 3.2 EQUIPMENT SUMMARY

This section briefly describes the types of equipment examined and factors considered in their design and costing. Also described are some factors not included in the analysis to either make it more manageable under time constraints or to avoid detail not warranted by the absence of site-specific data in the regional data bases used in the air quality and cost modeling.

The two broad classes of waste heat recovery equipment are those that preheat combustion air and those that heat the product. Equipment which heats combustion air is either a recuperator or a regenerator, depending upon whether the heat transfer medium flows continuously or cyclically. Equipment which heats the product for boilers, i.e., preheats the boiler feedwater, is an economizer. On tubestill heaters and other furnaces, equipment such as waste heat boilers can be installed to raise steam or to heat the product.

For heat transfer from clean gases with air preheat temperatures not exceeding present limits, convection recuperators always will be less expensive than radiation recuperators. Radiation recuperators are much larger than convection recuperators because radiant heat transfer requires a greater surface area. Convection units can have a much denser heat transfer surface than radiation units because convective heat transfer does not require gas passages with a large cross section.

Radiation recuperators are superior to convection units when flue gases are contaminated with particulates, when flue gas temperatures are very high, and when very high air preheat temperatures are desired. Convection units have smaller and more tortuous flue gas passages which are more likely to clog with particles and thus impair the performance of a convection recuperator than the passages in a radiation recuperator. Convection recuperator design limits it to air preheat temperatures less than 650°C (1200°F). Radiation recuperators can raise air temperatures several hundred degrees above 650°C. Air rarely has been heated to 650°C, but the economic advantages increase as fuel prices rise.

There are two types of regenerators: checkerwork and heat wheels. Checkerwork systems are used in very high temperature applications, such as continuous glass melting, open hearth furnaces, coke ovens, and batch steel reheat furnaces. Checkerwork systems can handle very high temperature flue gases and those that have substantial particulate carry-over. Heat wheels have been used to heat air to moderate temperatures using clean flue gases from large boilers and some tubestill heaters. When used with more contaminated, high temperature flue gases, heat wheels have had limited success. Their advantage over recuperators and checkerwork regenerators is that they are very compact and may be the only choice in crowded plants. The main problem with heat wheels is that the heat transfer media clog with particulates and are unsatisfactory in applications with inherently dirty flue gases.

Economizers, which heat boiler feedwater, are the preferred energy conservation technology for industrial boilers. They are more economical than combustion air preheaters because the energy absorbed goes directly into the product. Cold water is a better heat absorbing fluid than air; as a result, economizers are less expensive than air preheaters, while saving an equal amount of energy.

Tubestill heaters in petroleum and petrochemical plants are integrated into complicated processes. Sometimes products can be heated by flue gases and sometimes steam is raised in waste heat boilers.

The following design and cost analyses considered a variety of design alternatives for each equipment type. Among the factors considered are:

- The specific air and gas flow paths in a recuperator. Parallel flow limits the air preheat temperature to that of the cooled exiting flue gas, whereas using counterflow has the higher maximum air temperature of the flue gas entering the recuperator.
- Counterflow recuperators have a larger average temperature difference between the air and flue gas than parallel flow units; thus counterflow requires less heat exchanger area.
- Counterflow units have higher metal wall temperatures than parallel flow units, and, in many high temperature applications, the temperatures are beyond the design limits of available construction materials. In cases where design limits are not exceeded, higher quality and more expensive materials may be required for the smaller counterflow design.
- The needs for dilution air with hot flue gases were considered for convection units.
- Many convection units use a combination of crossflow and counter or parallel flow to simplify recuperator structural design.
- The limits of allowable flue gas and air side pressure drop were considered.

Some of the factors omitted from consideration in the designs are:

- The derating due to deposits forming on the heat transfer surfaces. (No data on average lifetime performance was found, and the calculations for specific furnaces would have too many assumptions to be credible. Therefore, all performances and resulting fuel savings are optimistic.)
- The effect of infiltrated air entering the flue gas system. (Many times air enters flue gas systems unintentionally. This infiltration will cool the gases and require the system to be larger than usual. Also, the infiltrated air will increase the flue gas volume,

so any design will need to be larger to meet any flue gas pressure drop requirements.)

- The data bases used to calculate equipment needs have flue gas temperatures measured at stack exits which are often hundreds, sometimes over 500°C, cooler than temperatures that would occur where a recuperator would be located. (This problem is especially serious on those furnaces which have pollution control equipment. As indicated by the waste heat inventory, about one-fourth of the potentially saved energy is on furnaces with pollution control equipment. This factor will tend to make the estimated equipment more expensive than it otherwise would be.)

- The largest omission is the site-specific installation costs. (For all units, a total cost about three times the equipment cost was used. The design data on available room, already installed heat recovery equipment, and similar factors are not found in the available data bases for computer analysis of all sources in a region. Without a computerized analysis it would be impractical to estimate the effects of the policies considered.)

- Major considerations are the effects of existing air preheat equipment. (It probably would need to be removed before more efficient equipment could be installed. The hot air from a new system could not be put in series with existing air preheat equipment because it would overheat the existing equipment. The only alternative is to put a new unit in series with an existing one in a parallel flow arrangement. This alternative is only practical if the materials of the existing unit do not require cooling the flue gas before it enters the existing units. If the flue gases are being cooled, the new unit in series probably would not have enough energy available to heat the air enough to be economical.)

- The cooling of the combustion air after it leaves the recuperator was ignored. (The amount of cooling depends upon the design of the combustion air system. Combustion air commonly has cooled several hundred degrees between the recuperator exit and the burner. This effect would tend to make the estimated costs too low because the fuel savings would be overstated.)

## 3.3 EQUIPMENT DESIGN

### 3.3.1 Radiation Units

#### 3.3.1.1 General Characteristics

Radiation recuperators generally are used for high temperature flue gas, typically from 1090 to 1430°C. At these high temperatures, radiative heat transfer dominates convective heat transfer. There are two basic configurations: the double shell recuperator and the cage recuperator. The double shell is more common and is made of two concentric cylinders (Figure 20 ). Flue gas flows through the inner cylinder while the combustion air flows

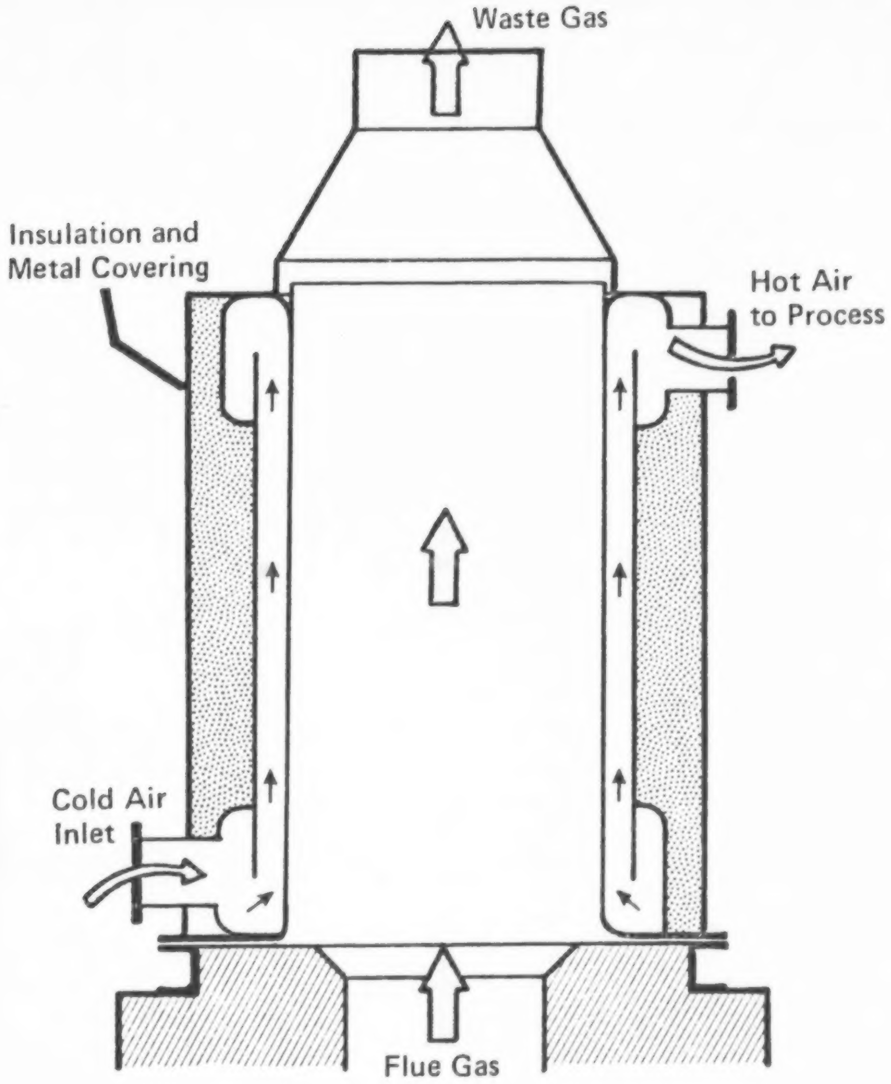
Waste Gas
Insulation and Metal Covering
Hot Air to Process
Cold Air Inlet
Flue Gas

Figure 20. Double shell radiation recuperator.

through the annulus between the two cylinders. The inner shell typically is 0.6 to 1.8 meters in diameter and the width of the annular region between the two shells normally is less than five centimeters. The cage recuperator consists of a ring of vertical pipes within a refractory-lined cylinder through which the flue gas flows (Figure 21 ). In cage recuperators, the combustion air flows through the pipes. Combustion air can flow in three basic patterns through the recuperator: parallel to the glas flow, opposite to the gas flow (counterflow), and a combination of the two patterns.

Parallel units have the flue gas and combustion air entering at the same end of the recuperator (Figure 22 ). The flue gas enters at the base section of the recuperator which does not become extremely hot because it tends to be cooled by the inlet air. As the flue gas travels through the recuperator, the gas temperature decreases and loses energy, while simultaneously, the air temperature gradually increases as it picks up energy from the flue gas (Figure 23 ). An important aspect of parallel flow units is that the preheated air temperature can never be greater than the flue gas temperature exiting the recuperator.

The counterflow pattern has the inlet air entering the recuperator at the opposite end from the inlet flue gases. The preheated air exits at the base (Figure 24 ). The base section of a counterflow recuperator is hotter than the base of parallel flow units because the high inlet gas temperatures are next to the exiting preheated air. The temperature distribution along the length of the counterflow recuperator creates a relatively constant temperature difference between the air and gas flows (Figure 25 ). In counterflow units, the limiting condition on the maximum attainable preheat temperature is the inlet flue gas temperature. Thus, for a given inlet flue gas temperature, counterflow recuperators can achieve higher combustion air preheat temperatures than can parallel flow units.

Combination flow units have parallel flow at the bottom section of the recuperator and counterflow at the top section (Figure 26 ). This flow pattern keeps the bottom section cool enough to enhance reliability while also allowing for higher temperatures than in a simple parallel flow design.

The relationship between air and gas temperatures as they flow through a recuperator is one of the primary factors in determining the overall heat transfer rates of the recuperator. The heat transfer rates are important because they ultimately determine the type and amount of materials used in the recuperator. The amount of heat transfer per unit area per hour (heat flux) determines the recuperator size. The higher the heat flux, the less area needed to achieve the desired preheat temperature. In general, the greater the temperature difference between the air and gas flows at a given point in the recuperator, the greater will be the heat flux. Since counterflow units have a greater average temperature difference between air and gas flow than parallel units, the counterflow recuperator will have a greater heat flux. Counterflow units, then, require less heat exchanger area than parallel flow units in order to achieve a given preheat temperature for the same inlet flue gas temperature and flow rates.

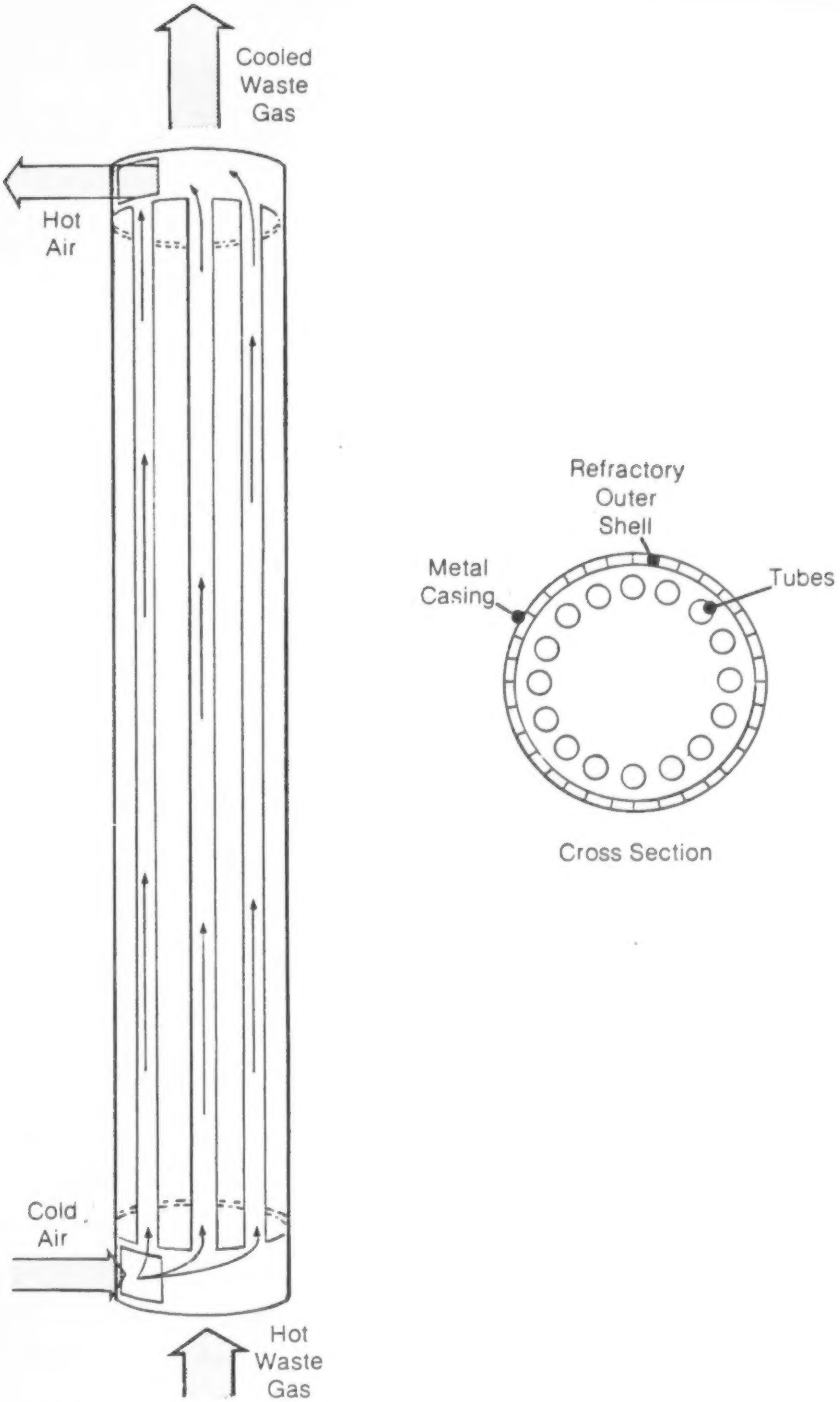
Cooled Waste Gas
Hot Air
Cold Air
Hot Waste Gas
Refractory Outer Shell
Metal Casing
Tubes
Cross Section

Figure 21. Cage recuperator.

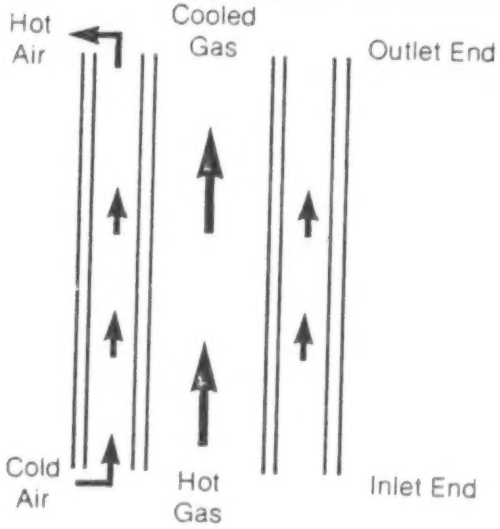
Hot Air
Cooled Gas
Outlet End
Cold Air
Hot Gas
Inlet End

Figure 22. Parallel flow pattern.

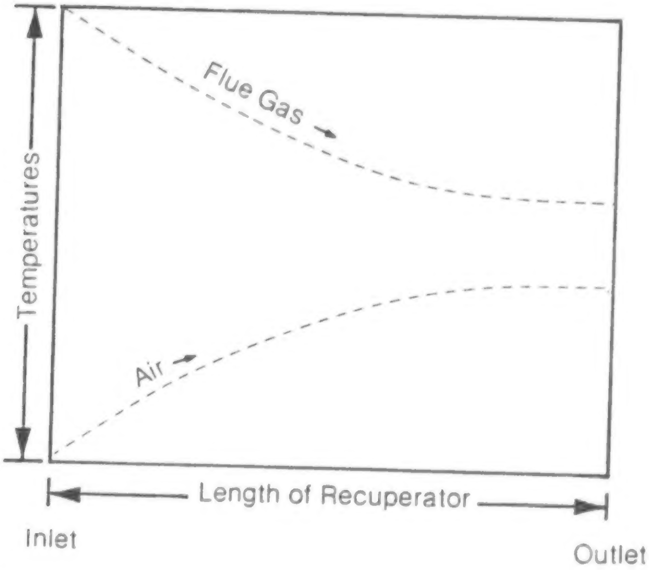

Figure 23. Parallel flow temperature patterns.

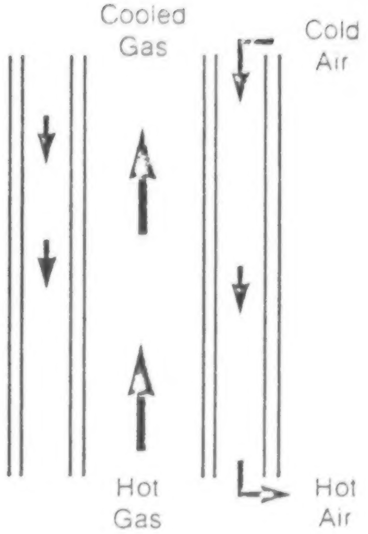
Cooled Gas
Cold Air
Hot Gas
Hot Air

Figure 24. Counterflow pattern.

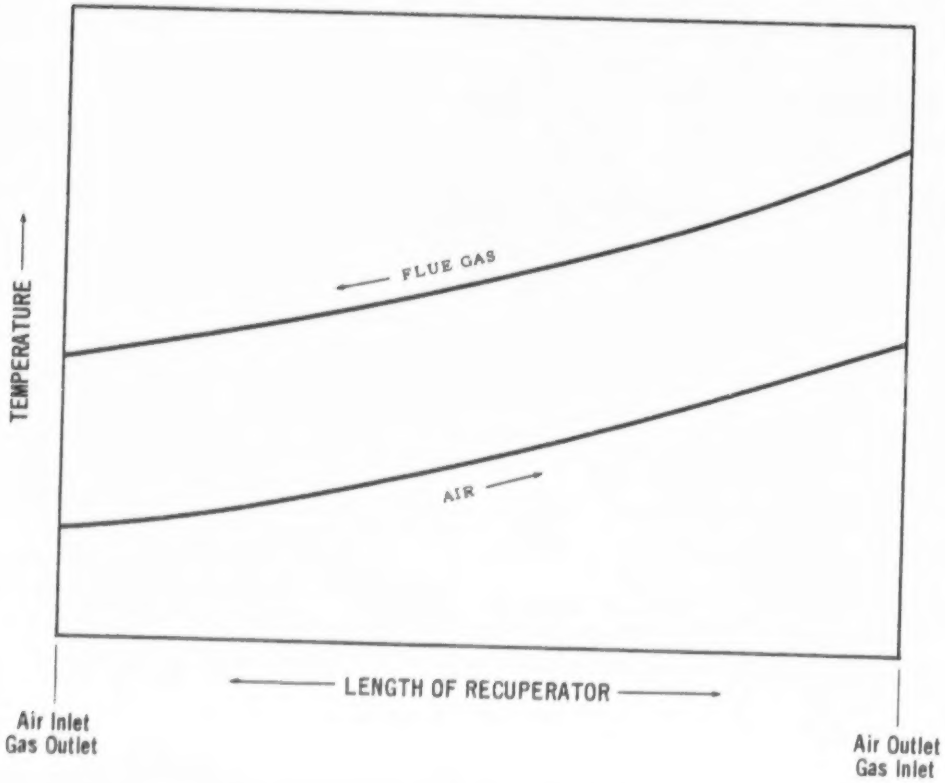

Figure 25. Temperature patterns in counterflow.

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TOP OF IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE

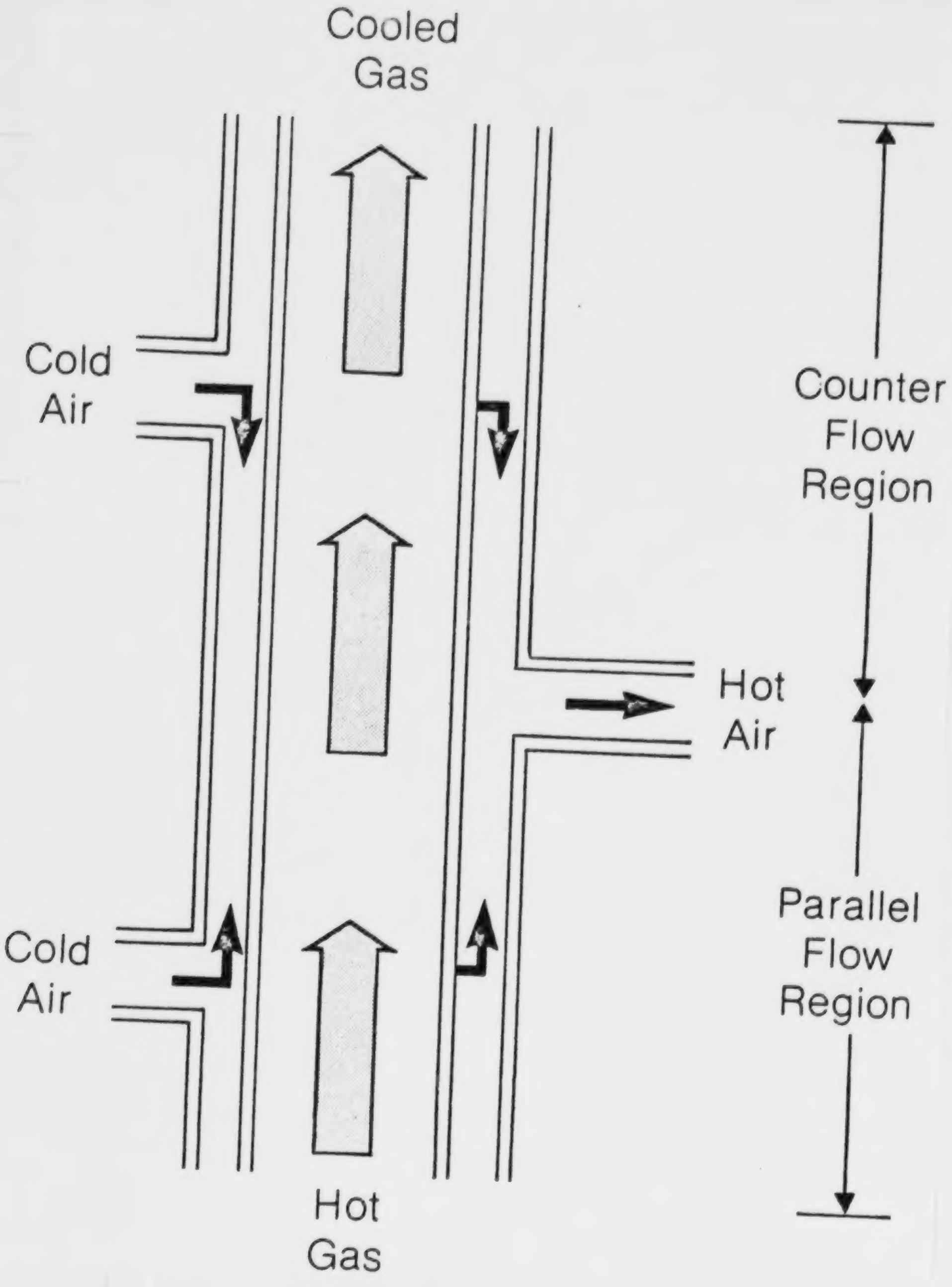
Cooled Gas
Cold Air
Counter Flow Region
Hot Air
Cold Air
Parallel Flow Region
Hot Gas

Figure 26. Combination flow pattern.

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3/8"
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There is an important design tradeoff between the amount of heat transfer area and material cost. High heat fluxes, due to high temperatures, reduce the required area, but also give high metal temperatures, which require using expensive alloys. Specifically, counterflow units have high heat fluxes, but also have high wall temperatures at their bases. The high inner wall temperatures in the base region can cause severe material problems requiring the more expensive alloys. In practice, most radiation recuperators are built in a parallel flow configuration because of the material considerations. For very high temperature units with flue gases in the range of 1320° to 1430°C (2400 to 2600°F), parallel flow design is used almost exclusively.

As previously mentioned, radiation recuperators generally are used for flue gas temperatures over 1090°C, although it has been found that some units are used at lower temperatures. Low temperature applications are not desirable since the radiant heat flux, which depends on the temperature of the gas raised to the fourth power, falls off rapidly as the gas temperature decreases. Thus, for low inlet gas temperatures, more heat exchanger surface area is required to obtain the same preheat temperature than with higher inlet gas temperature. For example, the area needed to get a preheat temperature of 430°C with an inlet gas temperature of 980°C is approximately twice that needed with an inlet gas temperature of 1200°C If an air temperature of 540°C is desired, the difference would be a factor of approximately 3.6.

In practice, a wide range of air preheat temperatures can be obtained. Currently, many units are being built for 430°C air preheat, although there are a number of units which obtain much higher preheat temperatures, up to around 700°C.

The size of a recuperator depends on the flue gas flow rate and temperature, the desired air preheat temperature, the allowable pressure drops, and the structural design decisions of the manufacturer. Radiation recuperators have been built for firing rates of fractions of gigajoules/hr and usually are not larger than 60 GJ/hr. The main constraint on the maximum firing rate is the physical size of the unit and the resulting structural stresses. For applications which require infeasibly large recuperators, two or more smaller units can be used in parallel. Units for small firing rates typically have dimensions as small as a 0.25 m inner shell diameter with a length of two meters. In large furnance applications, the units typically have an inner shell diameter of 2 to 3 meters and are 17 meters long.

### 3.3.1.2 Applications

Radiation recuperators are used for a wide variety of applications because they have a number of desirable characteristics. They operate at flue gas temperatures in the range of 980° to 1430°C which make it possible to obtain high preheat temperatures and achieve large fuel savings.

The simple cylindrical design of radiation recuperators allows them to operate well using dirty flue gases, i.e., flue gases with particulate carryover. In double shell units, the flue gas is virtually unobstructed as it flows through the recuperator so there is little chance of clogging the recuperator. The cylindrical design of radiation recuperators gives low pressure drops on the flue gas side and, thus, generally avoids needing additional fans for the flue gas exhaust system. Installing exhaust systems for flue gases can be complicated and requires additional energy to move the gases.

Specific applications of radiation recuperators include steel industry furnaces, such as soaking pits and reheat furnaces, decorative glass industry daytanks, aluminum melting furnaces, and unit melters for fiberglass. Table 25 illustrates the general operating parameters for typical radiation recuperator installations.

### 3.3.1.3 Potential Problems of Using Radiation Recuperators

While the design of radiation recuperators is based on well-known thermodynamic principles, construction techniques, and material properties, there are a number of design, construction, and operator errors which can result in major problems and financial loss. Equipment operated incorrectly can result in damage to the recuperator, the product, or the furnace, or loss of revenue due to a shutdown of the production line while the recuperator is repaired.

Design parameters must be specified accurately by the operator. The most common mistakes made in operating condition specifications are specifying average rather than peak temperatures and minimum flow rates. Often the appropriate measurements are not made or made incorrectly. Sometimes operators report average values for a cyclical operation. Important operating parameters include correct fuel/air ratio, consistent flue gas temperature without high temperature peaks, and consistent gas flow through the recuperator.

Radiation recuperators have been damaged severely when operated under conditions for which they were not designed. In one instance, the inner wall of a large radiation recuperator buckled when the operator allowed the burners to burn rich, i.e., higher than stoichiometric fuel/air ratio, while the dilution air system, which was used to cool the flue gas when it became too hot, was operating. As a result of the rich burning, there were unburned hydrocarbons in the gas. The dilution air injected to cool the flue gas to an acceptable temperature supplied enough oxygen for the unburned hydrocarbons to ignite and burn within the recuperator. The resulting high temperatures weakened the inner wall and it buckled. A completely new inner shell was required. The error was not in the design or construction, but in the operating conditions.

Another potential operating problem occurs if the furnace is turned down below the lowest design firing rate. As the firing rate decreases, the inner wall temperature of the recuperator will increase. If allowed to rise high enough, the wall will burn through. The decreased firing rate reduces the unit air flow which in turn reduces the rate of heat transfer from the wall to the air. The wall temperature increases because the flue gas-to-wall heat transfer rate does not decrease as much as the wall-to-air heat transfer

## TABLE 25. REPORTED INSTALLATION OF RADIATION RECUPERATORS

| UNIT | INDUSTRY TYPE | FURNACE TYPE | TEMP, °C (°F)[1] FG/PH | FIRING RATE,[2] GJ/hr (MMBtu/hr) | FUEL[3] SAVINGS(%) | (%)[4] | COST (1978$)[5] Equipment Cost | Installed Cost |
|---|---|---|---|---|---|---|---|---|
| $R_1$ | Glass | Batch Day Tank | $\frac{1200}{430}$ $\left(\frac{2200}{800}\right)$ | 2.1 (2.0) | 29 | 34 | 5,768 | 8,240 |
| $R_2$ | Glass | Batch Day Tank | $\frac{1200}{430}$ $\left(\frac{2200}{800}\right)$ | 2.4 (2.3) | 29 | 34 | 12,071 | 17,244 |
| $R_3$ | | | $\frac{1340}{474}$ $\left(\frac{2450}{885}\right)$ | 16.5 (15.6) | 37 | 34 | 23,500 | — |
| $R_4$ | | | $\frac{1340}{650}$ $\left(\frac{2450}{1200}\right)$ | 18.0 (17.1) | 44 | 47 | 50,000 | — |
| $R_5$ | | | $\frac{1150}{480}$ $\left(\frac{2100}{900}\right)$ | 18.0 (17.1) | 30 | 41 | 38,500 | — |
| $R_6$ | Fiber | Continuous | $\frac{1370}{650}$ $\left(\frac{2500}{1250}\right)$ | 19.4 (18.4) | 46 | 48 | 106,588 | 201,109 |
| $R_7$ | Aluminum | Batch Melting | $\frac{1070}{290}$ $\left(\frac{1950}{550}\right)$ | 23.7 (22.5) | 17 | 25 | 31,762 | 96,248 |
| $R_8$ | | | $\frac{1150}{450}$ $\left(\frac{2100}{850}\right)$ | 29.0 (27.5) | 29 | 38 | 50,000 | — |
| $R_9$ | | | $\frac{1200}{320}$ $\left(\frac{2200}{600}\right)$ | 28.3 (26.9) | 23 | 25 | 26,061 | 52,122 |
| $R_{10}$ | | | $\frac{1200}{430}$ $\left(\frac{2200}{800}\right)$ | 30.8 (29.2) | 29 | 34 | 40,103 | 80,206 |
| $R_{11}$ | | | $\frac{1200}{540}$ $\left(\frac{2200}{1000}\right)$ | 33.1 (31.4) | 34 | 43 | 66,640 | 132,280 |
| $R_{12}$ | Steel | Reheat Forge, Soak | $\frac{1200}{430}$ $\left(\frac{2200}{800}\right)$ | 33.4 (31.7) | 29 | 34 | 38,000 | 76,000 |
| $R_{13}$ | Aluminum | Batch Melting | $\frac{1090}{430}$ $\left(\frac{2000}{800}\right)$ | 35.9 (34.0) | 26 | 38 | 71,295 | 142,590 |
| $R_{14}$ | | | $\frac{1200}{320}$ $\left(\frac{2200}{600}\right)$ | 37.8 (35.8) | 23 | 25 | 49,980 | 99,960 |
| $R_{15}$ | | | $\frac{1200}{430}$ $\left(\frac{2200}{800}\right)$ | 41.0 (38.9) | 29 | 34 | 49,980 | 99,960 |
| $R_{16}$ | | | $\frac{1200}{540}$ $\left(\frac{2200}{1000}\right)$ | 44.1 (41.8) | 34 | 43 | 83,300 | 166,600 |
| $R_{17}$ | | | $\frac{1200}{320}$ $\left(\frac{2200}{600}\right)$ | 50.3 (47.7) | 23 | 25 | 42,007 | 84,014 |
| $R_{13}$ | | | $\frac{1200}{430}$ $\left(\frac{2200}{800}\right)$ | 54.5 (51.7) | 29 | 34 | 64,498 | 128,996 |
| $R_{19}$ | | | $\frac{1200}{540}$ $\left(\frac{2200}{1000}\right)$ | 58.7 (55.6) | 34 | 43 | 107,695 | 215,390 |

[1] FG is the reported flue gas temperature; PH is the reported air preheat temperature.

[2] Firing Rate is that before recuperation.

[3] Fuel Savings is the theoretical savings resulting from recuperation.

[4] % is a measure of the thermodynamic efficiency of the recuperator; $= \frac{T_{PH} - 25^\circ C}{T_{FG} - 25^\circ C} \times 100\%$

[5] Cost reported for years other than 1978 were normalized with the Fabricated Equipment component of CE Plant Cost Index, reported in Chemical Engineering, May 8, 1978.

rate.* Radiation units, therefore, must be designed carefully if they are to be used on cyclically operating furnaces.

In addition to operation errors which result in equipment failure, damages occur if recuperators are not used up to design capacity. In one instance, a parallel flow radiation recuperator that was designed for an entering flue gas temperature of 1260°C and an air preheat temperature of approximately 430°C had its inner wall destroyed at the base while in operation. The replacement unit was installed with a quenching unit to cool the flue gas to 930°C, which is well below the optimum temperature range of radiation recuperators. While the recuperator has not been destroyed since, neither has it operated as it was designed. The preheat temperature is 220°C below design specifications. Thus, while the operator has successfully obtained a long equipment life, he has limited the economic return on the recuperator investment to less than the maximum that would occur if temperature excursions were avoided.

#### 3.3.1.4 Equipment Design

The design of a radiation recuperator is based on two different modes of heat flow within the unit. One characterizes the energy transfer from the gas to the wall and the other characacterizes the energy transfer from the wall to the air (Figure 27 ). The gas-to-wall energy transfer is by radiation; the wall-to-air transfer is by convection. After these two quantities are calculated for a specific circumstance, the design can be completed. The detailed description of the heat transfer is in Appendix C. Below is a summary of the major model elements.

For the flue gas-to-wall energy transfer, the primary mode of heat transfer is radiation.** For a given radiator and absorbing surface, the energy transfer can be expressed by:

---

* Since wall-to-air heat transfer occurs by convection, it is a function of the air velocity. When the firing rate decreases, less combustion air flows through the annulus. The combustion air velocity then decreases. When the air velocity decreases, so does the heat transfer rate. However, the gas-to-wall heat transfer is primarily a radiative process which is predominantly a function of gas temperature and not gas velocity, except for a slight effect due to the residence time. When the firing rate is reduced, the volumetric gas flow rate will decrease, but the gas-to-wall heat transfer rate does not decrease very much except for the change in gas residence time. The system then will achieve a new equilibrium state with a higher inner wall temperature.

** Herein, all discussion will be based on the double shell recuperator because it is more commonly used. The basic design principles, however, apply to cage recuperators with the difference being that the combustion air flows through the tubes instead of the annulus.

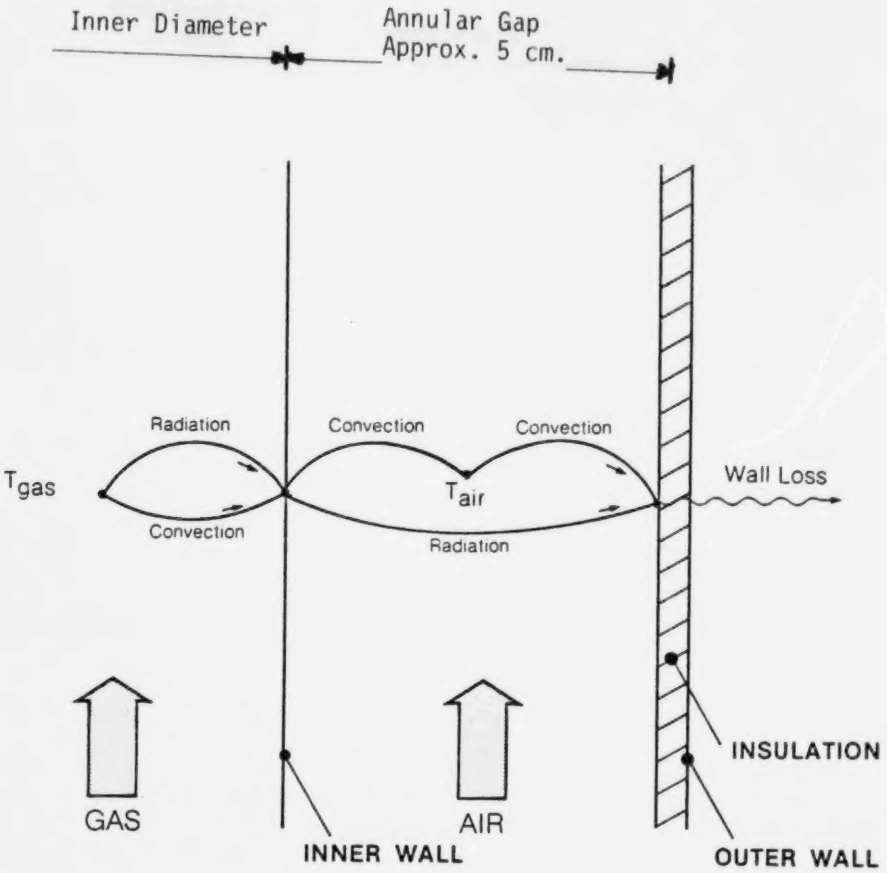
Inner Diameter
Annular Gap
Approx. 5 cm.
Radiation
Convection
Convection
$T_{gas}$
$T_{air}$
Wall Loss
Convection
Radiation
GAS
AIR
INSULATION
INNER WALL
OUTER WALL

Figure 27. Heat transfer diagram, radiation recuperator.

$$Q_r = GS\sigma \ A(T^4_{gas} - T^4_{wall}) \quad (1)$$

where $Q_r$ = rate of heat transfer by radiation

$GS$ = factor which takes the geometry, the emissivities, and the absorptivity of the flue gases and the inner wall into account

$\sigma$ = Boltzman constant

$A$ = the area of the inner wall to which the gases radiate

$T_{gas}$ = temperature of the gas expressed as an absolute temperature

$T_{wall}$ = temperature of the wall expressed as an absolute temperature

The radiative heat flux for the recuperator is calculated by dividing the heat flow by the wall area that absorbs the radiation.

In addition to radiative heat transfer, there also is convective heat transfer from the gas to the wall. Convective heat transfer can be expressed by:

$$Q_c = h_{gc} \ A(T_{gas} - T_{wall}) \quad (2)$$

where $Q_c$ = rate of heat transfer by convection

$h_{gc}$ = convective heat transfer coefficient

$A$ = area of the inner wall

$T_{gas}$ = temperature of the flue gas

$T_{wall}$ = temperature of the inner wall

The convective heat transfer coefficient ($h_{gc}$) describes the average rate of convective heat transferred per area per degree. The gas velocity is an important determining factor of the magnitude of $h_{gc}$. The convective component of the total heat transferred from gas-to-wall is small compared to the radiative component because most radiation units have relatively low flue gas velocities of less than 3 m/sec (10 ft/sec). Typically, the convective component ranges from a 25 percent high for high gas velocities and low gas temperatures to a 5 percent low for low gas velocities and high gas temperatures.

The heat absorbed by the inner surface of the inner wall is conducted to its outer surface. Because the thermal conductivity of a metal wall is high, there is only a negligible temperature drop from one side to the other.

The heat flow through the inner wall is transferred to the combustion air flowing through the annulus by two paths: directly, by convection from the inner wall to the air; and indirectly, by first being radiated from the inner wall to the outer wall and then being convected from the outer wall to the combustion air. Combustion air travels through the annulus at much higher velocities than the flue gas which causes the convection coefficient for the air to be comparatively larger. Radiative heat transfer between the wall and the air is very small in comparison to the convection component because of the low absorptivity of air.

An important consideration in shell recuperator design is the distance between the inner and outer walls. The necessary gap is designed by determining the desired air velocity through using the known air mass flow rate and the cross-sectional area of the annular air flow path. Generally, the smallest practical gap for a moderately-sized unit is around 2 centimeters.

To determine what heat exchanger area is required for a given set of conditions, the mass and heat balances throughout the recuperator must be calculated. Important determining factors are the input flue gas temperature, the desired outlet air temperature, the firing rate, the fuel type, the excess air percentage, and the allowable pressure drops, especially on the air side.

Since the heat transfer rate between two bodies depends so much on the temperature difference between them, it is important to consider the temperature distribution of the gas, air, and walls throughout the recuperator's length. One major determinant of the temperature distribution is the pattern of air flow. As discussed earlier, there are three basic patterns: parallel, counterflow, and a combination of the two.

Parallel flow creates a large temperature difference between the gas and the air at the recuperator's entry point, with the difference decreasing along the length of the recuperator as the gases get cooler and the air hotter. In contrast, counterflow units have a more constant temperature difference throughout the unit because the air and gas flow in opposite directions. If one considers the average temperature difference along the total recuperator length, the counterflow unit will have a greater difference. As a result of the relative temperature differences, the average heat flux for a counterflow unit will be greater than that for a parallel flow recuperator and, thus, given a flue gas inlet temperature, less area will be needed in a counterflow unit to attain a given air preheat temperature.

The flue gas and air temperature distributions also are important because they affect the choice of construction materials. For example, it may be advantageous to build counterflow units from the standpoint of total area required, but resulting high metal temperatures caused by the hot flue gas entering and the hot air exiting can create severe material problems. Few counterflow units are built for moderate to high gas and air temperatures because of the resulting material problems caused by the high wall temperatures.

### 3.3.1.5 Materials and Construction

Materials selection is determined mainly by stress levels, corrosive elements, and temperature extremes that heat exchanger surfaces are expected to encounter.

Strength of the material is an important factor on units which are both tall and have large diameters because considerable structural stresses are created. A significant force exists on the inner wall since the air pressure in the annulus is higher than that of the stack gas. Additionally, the inner wall must be made of a material that can withstand elevated temperatures.

The presence of corrosive agents also is an important factor in the choice of materials and design. While shell recuperators are more difficult to construct due to the higher tolerances required, they are better suited for dirty flue gas applications. Corrosion occurs when there are corrosive agents in the fuel, such as sulfur and vanadium (as in some residual fuel oils), or when the process itself involves corrosive agents, such as fluxing agents, which are sometime used in aluminum melters. At high temperatures the oxygen in flue gas can corrode some materials also.

A variety of alloys is used to accommodate the specific conditions experienced in certain applications. The material used can range from a low cost carbon steel to expensive alloys such as 309 stainless steel or Incoloy, both of which have better high temperature strength and are also more resistant to corrosion. As a result, the cost per unit area for radiation recuperators varies widely.

Besides thermodynamic and material considerations, limits are imposed by economic and technical factors involved in the fabrication of the unit. For example, the inner shell must be symmetrical in order to withstand the pressure stresses which could cause the inner wall to buckle. The inner shell also must be symmetrical so that local hot spots, or areas which have a higher temperature than the surrounding material, are avoided. Deformation of the inner shell will cause hot spots if there is a reduced air flow rate and/or a reduction in air velocity over a localized area. As a result of the altered air flow, the localized area will become hotter because it cannot transfer heat at the same rate as neighboring areas. Hot spots cause material degradation which can result in structural damage such as holes between the air and flue gas sides.

To obtain the required heat transfer area, there is a tradeoff between the height and the diameter of the unit. For all but some of the small recuperators, the shell is manufactured by rolling sheet steel into shape and welding the edges together. For diameters larger than 2 meters, it is difficult to symmetrically fabricate the inner wall to within the required tolerances. Instead of increasing the diameter to obtain the necessary tolerances, the unit height may be increased. For tall units, the recuperator may be built in sections to make fabrication and erection easier.

One way to solve the problems of structural stresses, hot spots, and the stress created by the pressure difference between the air and gas flows is to use a cage radiation recuperator design. The combustion air flows through pipes set in a ring pattern within a refractory-lined cylinder (see Figure 28 ). The pressure stresses are taken care of by choosing an appropriate tube wall thickness. Cage recuperators make it substantially easier to achieve a uniform gas and air flow so that hot spots are avoided. Since metals become weaker at higher temperatures, hot spots and pressure stress can become significant problems. Several manufacturers build cage recuperators for high air and gas temperatures (above 590 and 1260°C, respectively) and double shell recuperators for lower temperatures. With careful design and fabrication practices, however, shell recuperators also are feasible at high air temperatures.

### 3.3.1.6 Cost Estimates

Cost estimates for shell radiation recuperators were derived over a wide range of air and gas temperatures and firing rates. Shell units were modeled because they are used more widely and have an advantage over cage units for dirty applications.

For the purpose of this study, only parallel flow units are considered. Counterflow units are impractical at high air and gas temperatures because they are considerably more expensive to build. The high wall temperature at the flue gas entrance point requires that expensive alloys be used. In addition, at lower gas and air temperatures, the required heat exchanger areas for parallel and counterflow units converge so that the advantage counterflow units have in low temperature applications is smaller than the precision necessary for this analysis.

The equipment cost for a given set of operating conditions was found by calculating the required unit area and multiplying it by the specific cost per unit area. The area was calculated by a heat and mass balance based on the operating parameters of flue gas and air preheat temperatures, the firing rate of the furnace, the fuel type used, and the percent excess air (see Appendix C). Specific costs were estimated from analyses of radiation recuperators reported in the literature as well as information obtained at conventions and by meeting with vendors.

The accuracy of both the specific cost estimates and the calculations of required heat exchanger areas was checked by computing equipment costs for various units and comparing the costs to case examples. To reflect the range of different materials used for different applications, both upper and lower cost estimates were made. The upper cost estimate represents the use of expensive alloys under the most adverse conditions, while the lower estimate represents low grade alloys used for less than severe applications. Figure 3-9 shows that the case examples published by the vendors fall within the calculated cost estimates.

A cost estimate of $860 to $1300 per square meter of exchanger area was determined to be applicable for the lower operating range of radiation recuperators. For the higher range, where the gas temperature is greater than 1320°C and preheat temperatures are as high as 760°C a more expensive alloy must be used and the cost per unit area of exchanger area increases.

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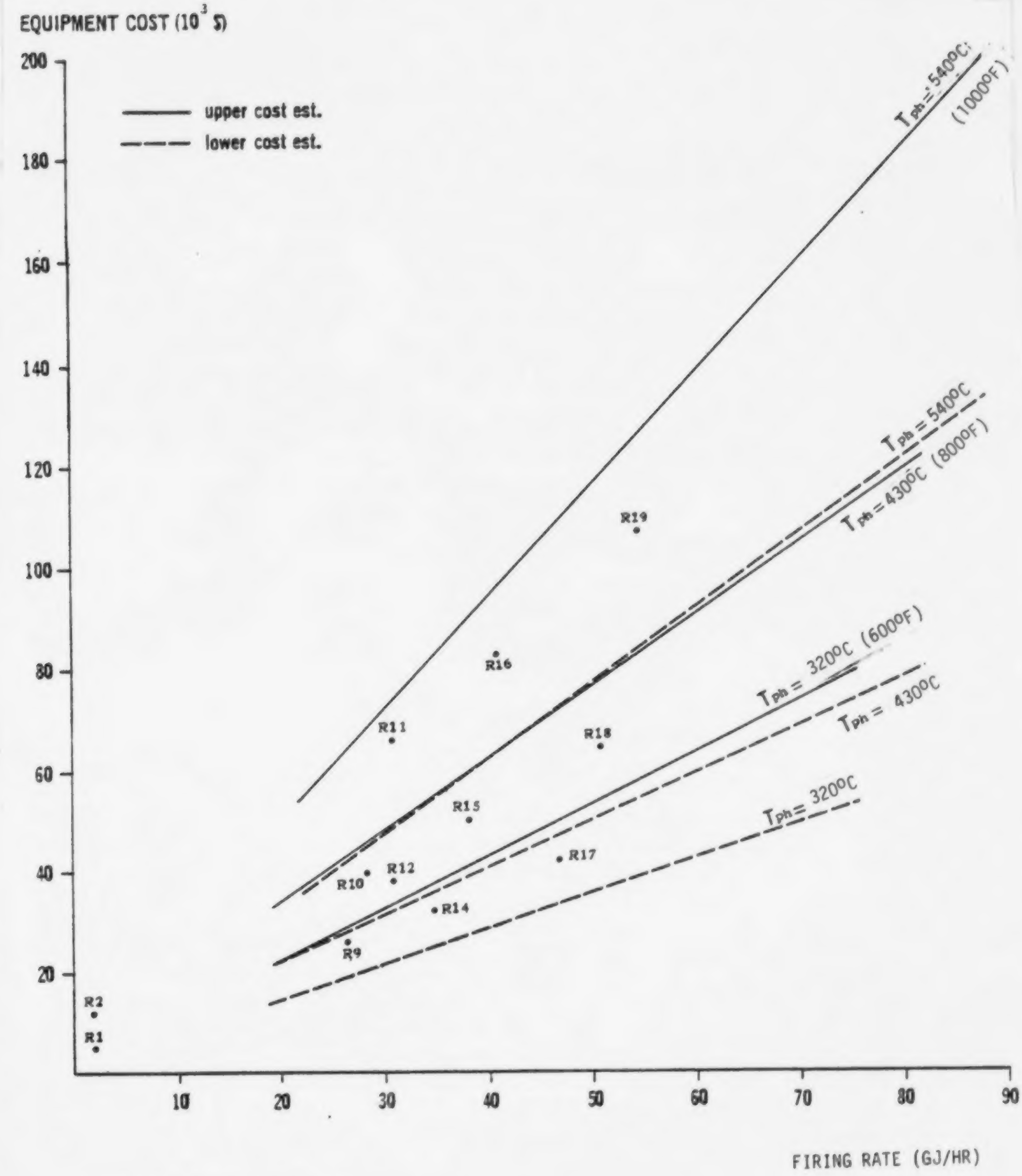

Notes: (1) Cost is the uninstalled equipment cost
(2) Firing rates are before recuperation

Figure 28. Radiation recuperator cost versus firing rate, flue gas temperature: 1200°C (2200°F)

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### 3.3.2 Convection Recuperators

#### 3.3.2.1 General Characteristics

Convection recuperators are used with lower temperature flue gases, generally below 1090°C (2000°F). Convection heat transfer dominates radiative heat transfer at these lower temperature ranges so radiation recuperators are not as well suited for low temperature flue gases as convection units.

There are a number of different convection recuperators, each having advantages under certain conditions. Most common are the metallic crossflow recuperators which are constructed with either tubes or pipes (Figures 29 and 30 ). At lower temperatures and for relatively clean applications, there are the metal crossflow plate units. Ceramic units are available and are well suited for high temperature applications. This section primarily covers the design and use of metallic tubular crossflow recuperators since they are used most commonly. Ceramic and metallic plate recuperators will be discussed in Section 3.3.2.7.

There are a variety of designs for metallic tubular crossflow recuperators. In tubular crossflow units, one fluid (either the combustion air or the flue gas) flows through tubes which are perpendicular to the flow path of the second fluid. Tubular recuperators are built in four basic configurations. If the air flows through the tubes, the tubes can either hang vertically in a horizontal canal or they can be placed horizontally in a vertical stack (Figure 29 ). If the flue gas flows through the tubes, the tubes are oriented vertically in a vertical stack or horizontally in a horizontal canal (Figure 30 ). Gas flows through the tube section when the flue gas is laden heavily with particulates because it is easier to clean inside the tubes than the labyrinth between the tubes. Furthermore, less of the particulate carryover falls out of the flue gas because the flow is not interrupted.

The simple crossflow pattern may be modified by using a sequence of passes (Figure 31 ). With each pass, the air in the pipes absorbs more of the enthalpy (heat energy) from the flue gas and a higher preheat temperature is achieved. For such a multi-pass system, the passes can be arranged in three patterns: each successive pass can occur downstream of the preceding pass (parallel configuration), each successive pass can be upstream of the previous pass (counterflow configuration), or there can be a combination of the two.

As stated earlier in this chapter, counterflow recuperators have several advantages over parallel flow recuperators. Given the same operating conditions, a counterflow configuration requires less heat exchanger area than a parallel flow unit. Because counterflow units can attain higher air preheat temperatures and a higher average temperature difference between the flue gas and air flows than parallel units, counterflow units have higher heat fluxes. However, an economic tradeoff exists between the reduced area of a counterflow recuperator and its more expensive construction materials. The higher metal temperatures could require more expensive materials; nonetheless, in many cases, the inlet flue gas temperatures are low enough so that it is economically attractive to build crossflow units in a counterflow configuration.

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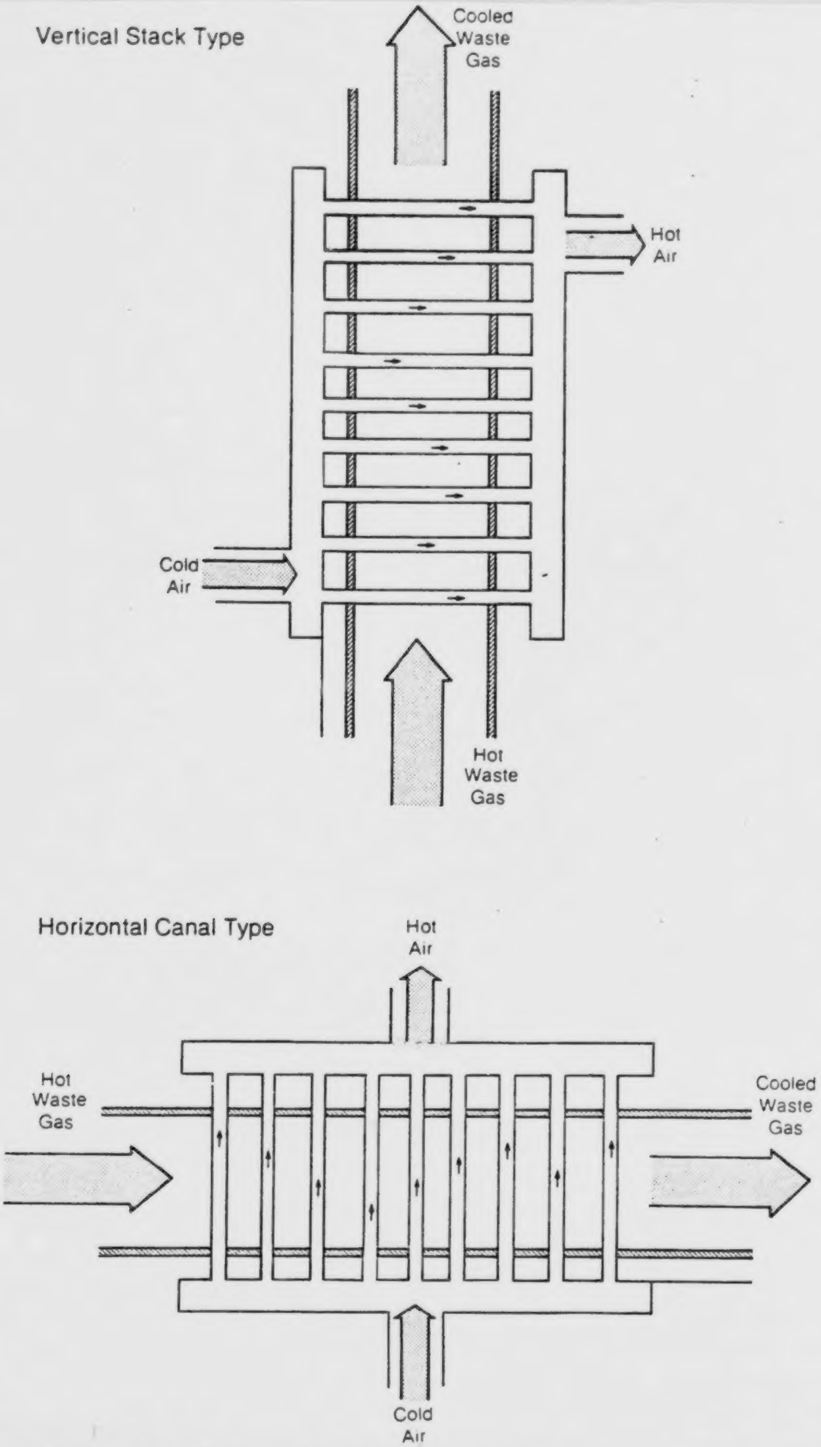
Vertical Stack Type
Cooled Waste Gas
Hot Air
Cold Air
Hot Waste Gas
Horizontal Canal Type
Hot Air
Hot Waste Gas
Cooled Waste Gas
Cold Air

Figure 29. Metallic crossflow tubular recuperators, air through tubes.

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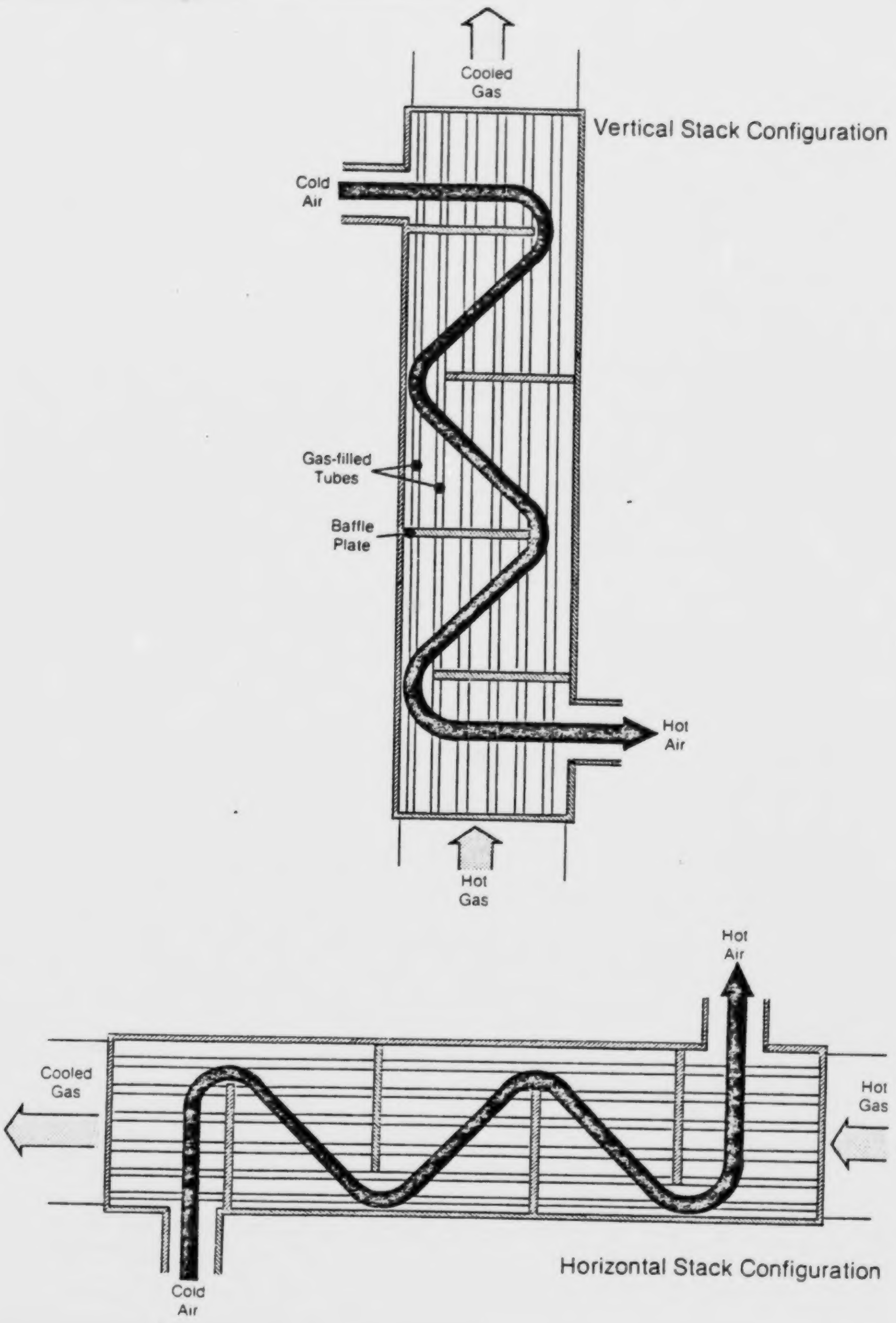
Cooled Gas
Vertical Stack Configuration
Cold Air
Gas-filled Tubes
Baffle Plate
Hot Air
Hot Gas
Hot Air
Cooled Gas
Hot Gas
Cold Air
Horizontal Stack Configuration

Figure 30. Metallic crossflow tubular recuperators, gas through tubes.

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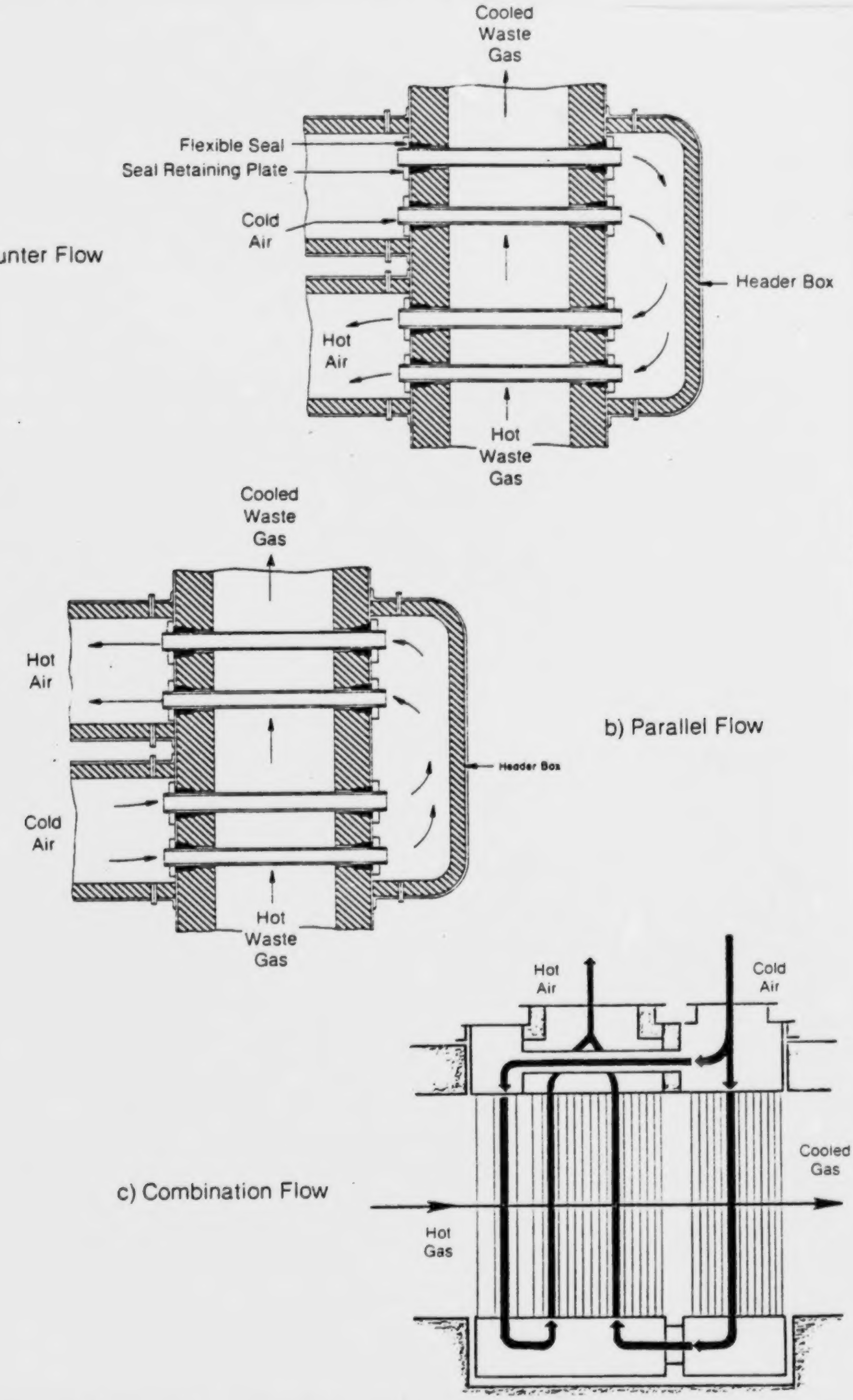
a) Counter Flow

b) Parallel Flow

c) Combination Flow

Cooled
Waste
Gas
Flexible Seal
Seal Retaining Plate
Cold
Air
Header Box
Hot
Air
Hot
Waste
Gas
Cooled
Waste
Gas
Hot
Air
Header Box
Cold
Air
Hot
Waste
Gas
Hot
Air
Cold
Air
Cooled
Gas
Hot
Gas

Figure 31. Multi-pass convection recuperators.

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Material considerations require convection recuperators to have flue gas inlet temperatures below a specific temperature limit, usually 980°C. The flue gas temperature limitation ensures that the metal temperature will be maintained within the design limits for the materials allowing lower grade alloys to be used in the recuperator. The temperature limit also restricts the amount of radiant heat transfer so that it is secondary to convective heat transfer.

In order to use convection recuperators for applications with flue gas temperature above the design limitation of the materials, the flue gas must be cooled. Although dilution air systems are the most common, water cooling is used also. Reducing flue gas temperatures before they enter the recuperator does not necessarily reduce the amount of fuel saved for the furnace system. The use of cooled flue gas does, however, limit the thermodynamically attainable air preheat temperature so that the maximum achievable is lower for a lower inlet flue gas temperature.

Many manufacturers have modularized the design of recuperators to some degree and only build single unites up to a certain size firing rate, typically around 50 GJ/hr. For applications with higher firing rates, recuperator modules are connected in parallel. Total capacities for convection recuperator systems range from firing rates of a few gigajoules/hr for very small furnances to several hundred gigajoules/hr for very large furnaces, such as large steel reheat furnances.

### 3.3.2.2 Applications

Convection recuperators have unique characteristics which make them suitable for a wide variety of applications. The important characteristics considered in using convection units are the attainable air preheat temperatures, the pressure drops through the units, the limitations for use in dirty flue gas applications, and the advantages of using convection recuperators on cyclical furnace operations.

Even though gas inlet temperatures usually are limited to a maximum of 980°C, convection recuperators are capable of achieving fairly high preheat temperatures, typically up to around 650°C. Thermodynamically, it is possible to achieve higher preheat temperatures, but equipment costs increase rapidly as the higher temperatures are approached. Figure 32 illustrates the increase of equipment cost as a function of preheat temperature.

One constraint which affects the overall economic feasibility of using tubular convection recuperators is the pressure drop of the flue gas flow through the unit. Since the recuperator has tubes placed in the flow path of the flue gas stream, there can be a significant pressure drop in the gas flow. If the pressure drop through the recuperator is large enough, the furnace system will require a greater amount of draft. In general, it is very expensive to create additional draft, especially if it needs to be relatively lare, on the order of five cm of water column.* For this reason, convection crossflow tube recuperators generally are designed to have pressure drops, on the order of 1 to 2.5 cm of water column. Limiting the

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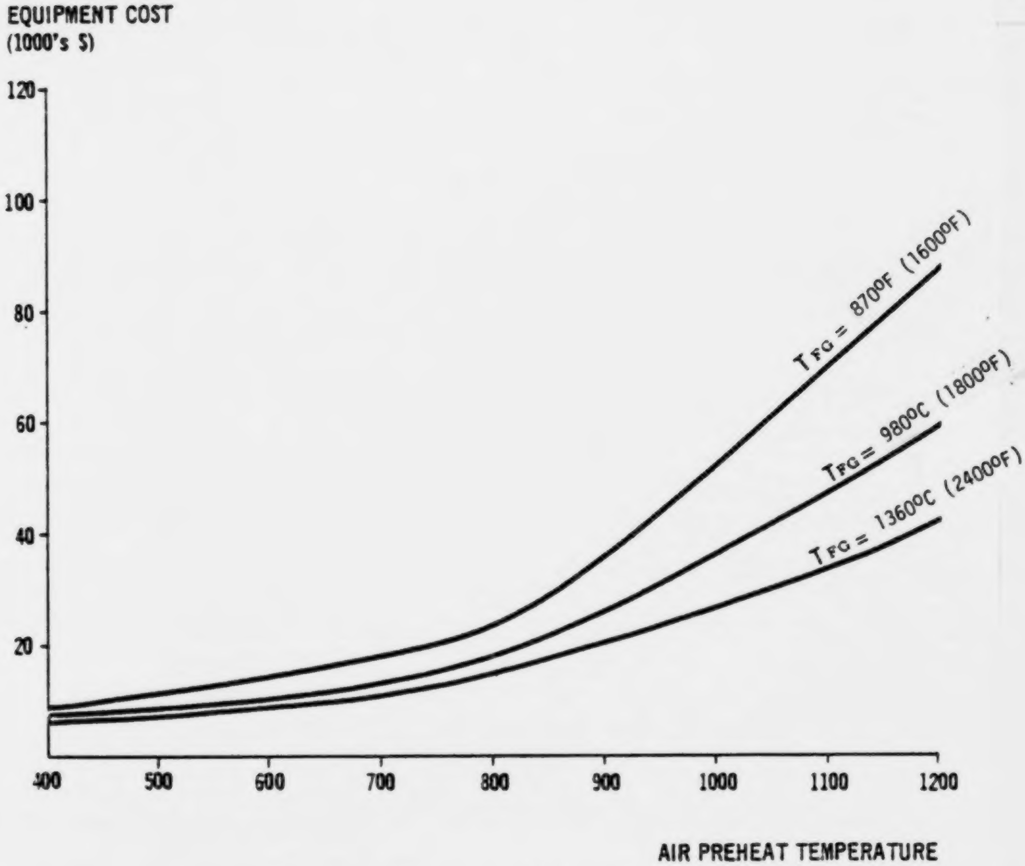

Notes: (1) Cost is the uninstalled equipment cost

Figure 32. Convection recuperator cost versus air preheat temperature. Firing rate before recuperation: 30 GJ/hr.

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flue gas pressure drop affects design parameters such as tube spacings, number of tubes, and tube geometry which ultimately affect the unit's total cost.

Tubular convection recuperators perform poorly with flue gases that have large amounts of particulate carry-over. At high velocities, particulates are entrained by the flue gas. When the flue gas flow is interrupted by the crossflow tubes, fouling can occur. The tubes interrupt the flue gas flow which alters the gas velocity and causes stagnation points in the gas flow. With the disruption, the particulates are no longer entrained and they either coat the heat exchanger surface, which restricts heat transfer, or they clog air passages, which restricts flue gas flow.

The coating of surfaces and clogging of flow paths within the recuperator will cause it to lose effectiveness, thereby lowering the attainable preheat temperature for a given set of conditions and possibly increasing material degradation if the clogged areas cause hot spots. In addition, material degradation can be exacerbated if corrosive agents are present and heat exchanger surfaces are coated as a result of either reduced gas velocities or stagnation.

One remedy for poor performance under dirty conditions is to allow the flue gas to flow through the unit's tubes. Such units perform well because the flue gas flow is not interrupted. However, the allowable pressure drop on the flue gas flow severely limits the allowable gas velocities and causes the convective heat transfer coefficient on the gas side to be relatively small. The required tube size for gas flow through the tube units, as a result, is much larger than for combustion air flow through the tube units for the same operating conditions. Furthermore, sticky material still can adhere to the inside tube surfaces inspite of the unobstructed flow path.

Due to the lower temperature ranges at which they operate, convection recuperators are better suited than other heat recovery devices for furnaces which are operated cyclically, such as batch furnaces. In a batch furnace, the load is inserted and heated to the desired temperature. After the needed processing time, the load is discharged and the furnace may cool. A new load then is inserted and the heating cycle is repeated.

If a furnace spends a significant amount of the cycle time heating to a given temperature, much of the resulting flue gas will be below the maximum flue gas temperature of the cycle. As a result, even if the maximum flue gas temperature is very high (above 1090°C) it is possible that during much of the cycle the flue gas temperature is lower. For such conditions, convection units are more appropriate than radiation units because radiation units have considerably lower effectiveness for flue gas temperatures under 1090°C than do convection units. In many cases, convection recuperators also can provide

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* Draft can be created for a furnace system by: (1) increasing stack height, (2) adding hot flue gas fans, and (3) utilizing high velocity air ejected near the top of the stack to create an induced draft such as the "ejector" system used in the Morgan-Isley system. All of these options can add greatly to the capital cost of the system.

higher preheat temperatures throughout the cycle because a greater amount of the cycle usually results in relatively low flue gas temperatures.

Convection units are well suited for a broad range of applications. They perform well at low temperature ranges, although, if a dilution air system is used, convection units can be used on high temperature processes. Convection recuperators typically have been used in the steel industry on soaking pits, preheat furnaces, and heat treating furnaces; on waste gas or sludge incinerators; and, more recently, in the aluminum industry on melting furnaces. Table 26 illustrates a number of applications including data on the temperature ranges, firing rates of the furnace system, and cost of equipment.

### 3.3.2.3 Equipment Design

To design a convective recuperator, the various heat flow paths must be considered. The primary heat flow paths are from the gas to the outer surfaces of the tubes and from the inner surface of the tubes to the air. Both heat fluxes are predominantly convective. The detailed description of the heat flow model used is in Appendix C. Below is a summary of its major points.

Convection recuperators can be characterized by an overall heat transfer coefficient known as $\bar{U}$. The whole system is described in terms of $\bar{U}$ by the following equation:

$$Q_t = (\bar{U})\,(A)(\Delta T_{lm}) \qquad (3)$$

where $Q_t$ = rate of heat flow transferred from the gas through the walls of the tubes to the air

$\bar{U}$ = characteristic conductance of the whole unit

$A$ = total area through which heat is transferred

$\Delta T_{lm}$ = logarithmic mean temperature difference

If the value of $\bar{U}$ is known for the specific system, and values of $Q_t$ and $\Delta T_{lm}$ are calculated from the operating conditions, then the required heat exchanger area can be found.

The system's average conduction coefficient ($\bar{U}$) is determined by calculating the conduction coefficients for the three heat flow paths in the recuperator. The three paths are (a) from the flue gas to the outer tube walls, (b) from the outer tube walls to the inner tube walls, and (c) from the inner tube walls to the combustion air. The conduction term for metal walls can be neglected because metals offer very little resistance to the flow of heat. $\bar{U}$ is then expressed by:

$$\bar{U} = (1/h_{gc} + 1/h_{ac})^{-1} \qquad (4)$$

where $h_{gc}$ = the convective coefficient for the heat flow from the gas to the outer tube surface

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## TABLE 26. REPORTED INSTALLATION OF CONVECTION RECUPERATORS

| UNIT | INDUSTRY TYPE | FURNACE TYPE | TEMP °C(°F)[1] FG/pH | FIRING RATE,[2] GJ/hr (MMBtu/hr) | FUEL[3] SAVINGS(%) | (%)[4] | COST (1978$)[5] Equipment Cost | Installed Cost | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| $C_1$ | Steel | Batch Forge | $\frac{820}{540}\left(\frac{1500}{1000}\right)$ | 19.7 (18.7) | 25 | 65 | 38,000 | 76,000 | |
| $C_2$ | | | $\frac{950}{430}\left(\frac{1750}{800}\right)$ | 26.0 (24.6) | 24 | 43 | 21,500 | -- | Installed cost not reported |
| $C_3$ | Steel | Batch Forge | $\frac{820}{540}\left(\frac{1500}{1000}\right)$ | 28.2 (26.7) | 25 | 65 | 45,000 | 90,000 | |
| $C_4$ | | | $\frac{1000}{540}\left(\frac{1830}{1000}\right)$ | 38.6 (36.6) | 29 | 53 | 50,000 | -- | Installed cost not reported |
| $C_5$ | Steel | Batch Forge | $\frac{820}{540}\left(\frac{1500}{1000}\right)$ | 42.2 (40.0) | 25 | 65 | 55,000 | 110,000 | |
| $C_6$ | Steel | Batch Reheat | $\frac{980}{540}\left(\frac{1800}{1000}\right)$ | 57.5 (54.5) | 34 | 54 | 90,000 | 120,000 | $T_{FG}$ diluted from 1200°C |
| $C_7$ | | | $\frac{980}{430}\left(\frac{1800}{800}\right)$ | 69.4 (65.8) | 24 | 42 | 47,000 | -- | Installed cost not reported |
| $C_8$ | Steel | Batch or continuous rehe | $\frac{980}{540}\left(\frac{1800}{1000}\right)$ | 159.5 (151.5) | 34 | 54 | 150,000 | 200,000 | $T_{FG}$ diluted from 1200°C |
| $C_9$ | Steel | Continuous Reheat | $\frac{980}{450}\left(\frac{1800}{850}\right)$ | 137.2 (130.0) | 25 | 45 | 160,000 | 200,000 | |
| $C_{10}$ | | | $\frac{980}{480}\left(\frac{1800}{900}\right)$ | 176.8 (167.6) | 26 | 48 | 78,600 | -- | Installed cost not reported |
| $C_{11}$ | | | $\frac{890}{450}\left(\frac{1650}{800}\right)$ | 172.6 (163.6) | 23 | 46 | 78,600 | -- | Installed cost not reported |
| $C_{12}$ | Steel | Continuous Reheat | $\frac{1090}{430}\left(\frac{2000}{800}\right)$ | 262.7 (249.0) | 26 | 38 | 140,000 | 280,000 | |

---

[1] FG is the reported flue gas temperature; PH is the reported air preheat temperature.

[2] Firing Rate is that before recuperation.

[3] Fuel Savings is the theoretical savings resulting from recuperation.

[4] % is a measure of the thermodynamic efficiency of the recuperator; $\frac{T_{PH} - 25^{\circ}C}{T_{FG} - 25^{\circ}C} \times 100\%$

[5] Cost reported for years other than 1978 were normalized with the Fabricated Equipment component of CE Plant Cost Index, reported in Chemical Engineering, May 8, 1978.

$h_{ac}$ = the convective coefficient for the heat flow from the inner tube surface to the air

Both coefficients depend on the air and flue gas velocities, the flow path geometry, and the physical characteristics affected by temperature such as viscosity and density. Important physical and geometric conditions which determine $\bar{U}$ are the number of tubes, the tube's inner and outer diameter, the spacing between the tubes, the orientation of the tubes, i.e., whether they are staggered or in rows, and the gas and air flow rates and temperatures. Appendix C provides the equation which gives the functional forms of $h_{gc}$ and $h_{ac}$.

The other parameter of equation 3 which determines the required heat exchanger area is the logarithmic mean temperature difference ($\Delta T_{lm}$). $\Delta T_{lm}$ is the factor which takes into account the temperature distribution throughout the unit. The larger the difference between gas and air temperatures for a given location, the higher is the heat flux. Since the gas and air flow patterns determine the temperature distribution, they also determine what the $\Delta T_{lm}$ will be. For crossflow units in a parallel configuration, the logarithmic mean temperature difference of the unit is related to the value which would result from parallel flow, except for a multiplicative constant.* The crossflow units in a counterflow configuration have, in turn, a logarithmic mean temperature difference which is related to that for a counterflow configuration. For a given gas inlet and air inlet and outlet temperature, the $\Delta T_{lm}$ for cross-pass units in a counterflow configuration is greater than the $\Delta T_{lm}$ for a unit in a parallel configuration. The counterflow configuration units, therefore, will have higher heat fluxes and require less area than other flow patterns. On the other hand, the counterflow unit also will have higher wall temperatures.

The variables which determine how much heat exchanger area is required are the heat flow rate transferred from the gas-to-air ($Q_t$), the average unit conduction coefficient ($\bar{U}$), and the logarithmic mean temperature difference ($\Delta T_{lm}$). Typically, values for $\bar{U}$ range between a low of 30 and a high of 60 $W/(m^2)(^oC)$** for combustion air through the tube units. Based on an analysis of a number of convection recuperators and discussions with equipment vendors, teh representative value of $\bar{U}$ chosen for this study is forty $W/(m^2)(^oC)$. It was assumed that the modeled unit would be in the counterflow configuration with the flue gas inlet temperature constrained to 980°C, since, as mentioned before, the heat fluxes are greater and the resulting wall temperatures are manageable. For applications with a higher flue gas temperature, the use of dilution air was assumed and the required changes in flue gas inlet mass flow were made. Appendix C provides a derivation of the model used for convection recuperators.

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* The calculated $\Delta T_{lm}$ for crossflow units in a counterflow configuration is equivalent to that for a parallel flow unit for the same conditions except for a multiplicative constant. The constant generally varies between 0.5 and 1.0 and is temperature dependent.

** 5 to 10 $Btu/(hr)(ft^2)(^oF)$

### 3.3.2.4 Materials and Construction

Two factors which greatly affect recuperator cost are the type of material and construction practices used in manufacturing the unit. The material used in convection recuperators is expected to withstand the high temperatures, the thermal stresses experienced under normal operating conditions and thermal cycling, and the corrosion due to the presence of corrosive agents.

The most important considerations in making construction material decisions are the temperature distributions and corrosive conditions. For high flue gas and air preheat temperatures, various stainless steel alloys are used, typically 304 or 309. When the flue gas is particularly hot and contains particulate carry-over, both a higher grade alloy, i.e., HD or HK cast stainless steel, and thicker walls are required. For relatively low flue gas temperatures (below 820°C), carbon steel may be used. Vendors use a variety of different pipes and tubes. For example, one manufacturer commonly uses very thin-walled pipes, such as schedule 10, and 304 or 309 stainless steel. Another manufacturer commonly uses centrifugally cast tubes of HD or HK alloy with a wall thickness of 0.8 cm. The latter is almost double the cost of the 304 schedule 10 pipe.

Thermal stresses are also important. Excessive stress can cause warping of the tubes and, under some conditions, can cause the tubes to crack or pull away from the tube sheets. Thermal stresses are created by an uneven temperature distribution throughout the unit, due to the crossflow pattern and possible unevenly distributed gas flow, and thermal cycling as the tubes heat and cool. These stresses usually can be handled by proper design. For example, a floating tube sheet can be used which allows for the thermal expansion of the tubes. It is important, though, that the materials chosen have the appropriate physical properties for the expected temperatures and stresses. Also, the physical dimensions of the tubes must be taken into account. For example, it is not necessarily true that tubes with thicker walls are more resistant to thermal stresses.

Metallic tubular units are built in a number of different configurations, such as having the tubes oriented horizontally in a vertical stack or vertically in a horizontal canal. The primary factor determining which configuration is used is the availability of space for the equipment. Another important factor in determining equipment configuration is the way the designer allows for the thermal expansion. Some manufacturers bend the tubes into an S or W shape to allow for thermal expansion. In this case, the tube ends are anchored firmly to the frame. Other manufacturers either use a floating tube sheet or anchor the tubes at only one end. In the latter design, the tubes hang vertically and each tube has a u-bend, or similar arrangement, to carry the air in and out of the canal.

Since tubular convection recuperators use materials which can be mass produced and handled easily in the shop, the total manufacturing costs generally are lower than radiation units. Construction of tubular recuperators involves constructing the tube sheets, welding the tubes into place, and building the surrounding structure, including the connections between different passages. Construction of the unit becomes more difficult and expensive if a large number of tubes are used and they are close together.

### 3.3.2.5 Cost Estimates

Convection unit costs were estimated by first subtotaling the cost of materials and labor and then adding a percentage of the subtotal to cover overhead and profit. For a typical unit, several vendors indicated that the cost per tube installed (not including the material costs) ranged between $60 and $100 per tube and that overhead and profit were approximately 25 percent of labor and materials. Another approach was taken to substantiate manufacturers' quotes. Tube vendors reported that tube costs varied greatly depending on the tube's diameter, wall thickness, length, material, and type. Total equipment cost per square meter of exchanger area was found to range between $430 and $645.*

Using the assumed value of $\bar{U}$, which was determined by the heat transfer analysis and the specific cost estimates of $430/m$^2$ for the low air preheat temperature and $645/m$^2$ for higher preheat temperatues, a table of costs for various air outlet temperatures, gas inlet temperatures, and flow rates was developed. In order to confirm the validity of both the U and specific cost assumptions, a few case examples were compared to the calculated equipment costs (Figure 33 ).

### 3.3.2.6 Metallic Plate and Ceramic Recuperators

In addition to the metallic tubular recuperator, convection recuperators are constructed in a metallic plate design as well as in ceramic tube and plate designs. Each type has features which determine its applicability to different conditions.

The typical plate recuperator is a crossflow unit where combustion air and flue gas flows are separated by the plates. To increase the amount of heat transfer, the plates can be corrugated. Metallic plate units are relatively small in capacity; usually each unit handles less than one gigajoule/hour. For larger furnace applications, units can be connected in parallel. Metallic plate recuperators are suited primarily for low temperature applications in the 150 to 320°C range. At higher temperatures, the sealing material breaks down and the metal plates warp. As a result, leaks occur between the flue gas and combustion air. The flue gas must be relatively clean or else the passages will clog, especially in corrugated plate units.

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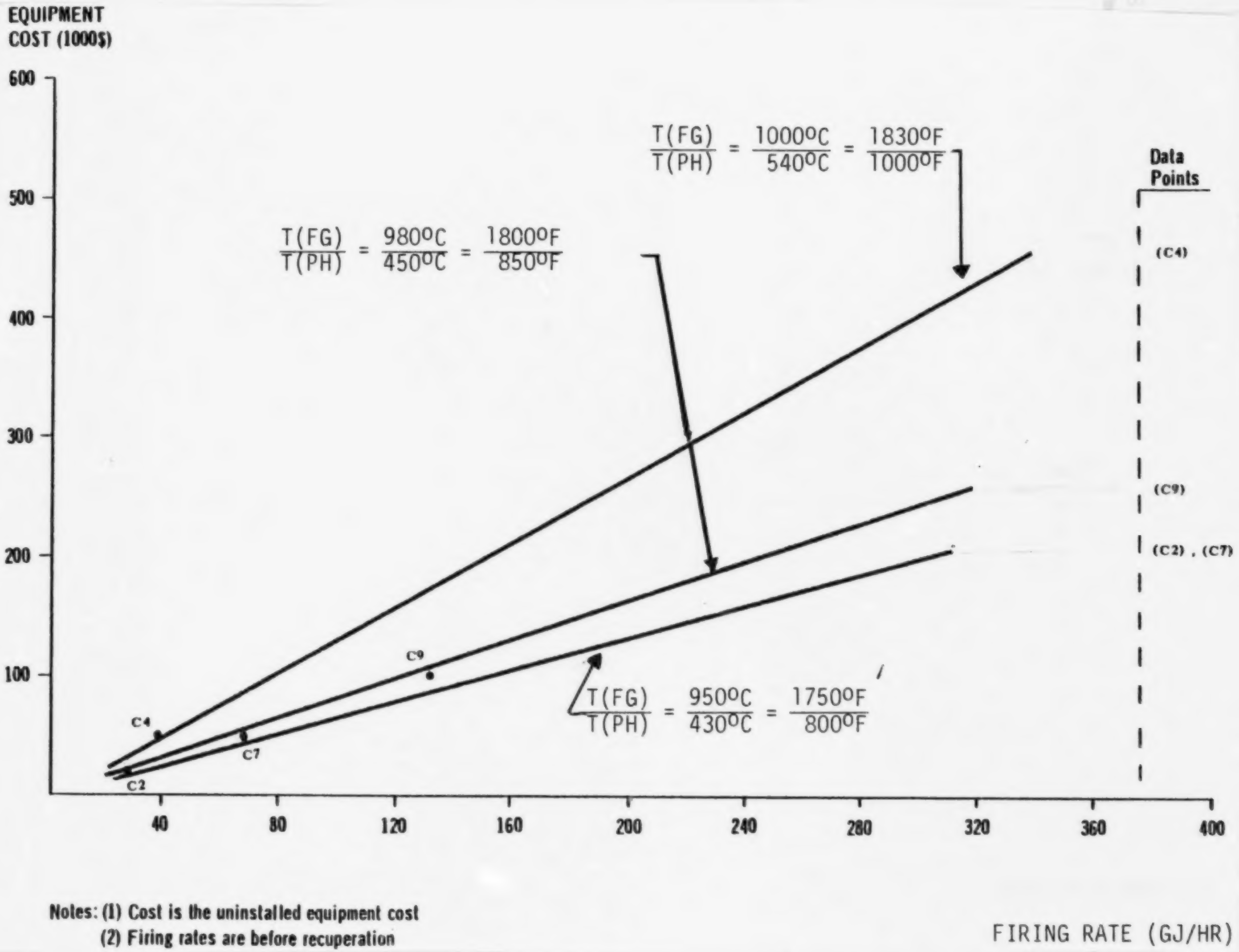
* The lower cost estimate is based on a unit constructed out of 8.9 cm nominal size stainless steel pipe (304 stainless steel, schedule 10). The higher figure is based on a centrifugally cast 8.9 cm outer diameter, 0.8 cm wall thickness, and tube of HD stainless steel.



Notes: (1) Cost is the uninstalled equipment cost
(2) Firing rates are before recuperation

Figure 33. Convection recuperator cost versus firing rate.

Because of the size and temperature limitations, metallic plate recuperators are suited primarily for small furnaces and low temperature applications which have relatively clean flue gases. One particularly useful application is to use preheated air for paint drying applications where the flue gases are loaded with combustible solvents.

Recuperators also can be manufactured out of ceramic material. The advantage of using ceramic materials is their stability at high temperatures. At high temperatures, ceramics are more structurally sound and resistant to warping from thermal cycling. As a result, ceramic units generally do not require dilution air systems to protect heat exchanger materials and hold up better when the furnace experiences temperature excursions. The pressure drop across the plate is relatively small. Even though ceramic plates are generally more resistant to corrosive attack than metals, heavy amounts of particulates will cause clogging.

The major problem with ceramic units, however, is that it is difficult to achieve a good gas-tight seal between surfaces. As a result, leaks between the air and gas flow can develop which reduce the recuperator's effectiveness. Leakages of 8 to 60 percent of the combustion air into the flue gas are reported.[1] Some ceramic plate units, such as the Chapman-Stein recuperator, have reduced the leakage problem, but it still exists and can be serious depending upon unit operation.

Another ceramic plate unit is the Cuberator marketed by Thermal Transfer, Inc. and others. It is a cubic ceramic structure with flow passages formed by the plates. The air and gas flows are perpendicular to each other in a crossflow configuration. Capacities for the units range from 0.25 to 1.5 GJ/hr, but multiple units may be used in parallel to obtain greater capacities. Flue gas temperatures can range from 820 to 1150°C and air preheat temperatures of 370° to 540°C can be obtained. Higher preheat temperatures are possible if the units are used in a series. Cuberators are suited for small furnaces such as radiant tubes, forges, and heat treated furnaces.

Tubular ceramic units also have been developed. Much like metallic units, the ceramic tubular units consist of a support frame in which the ceramic tubes are held. Such units operate under the same principles as the metallic tube recuperators. Manufacturers use a strong ceramic material at high temperatures, up to 1430°C, which is resistant to corrosive agents and has a low coefficient of thermal expansion.

The use of ceramic tubes, rather than plates, enables manufacturers to produce large capacity units. Depending on flue gas and air temperatures, firing rates for single modules can have an upper limit ranging from 70 to 100 GJ/hr. Applications with high flue gas temperatures of up to 1370°C can be used and preheat temperatures as high as 650°C can be achieved. Ceramic tube units have been utilized successfully on a number of different steel furnaces.

### 3.3.3 Regenerators - Heat Wheels

#### 3.3.3.1 General Characteristics

Heat wheels are heat absorbing, disk-shaped objects which are rotated through separate flows of combustion air and flue gas (Figure 34). They are constructed out of either metallic or ceramic material. The hot flue gas passing through a disk section heats the disk. Then when the disk is rotated into the combustion air flow, it loses heat to the air.

There are two basic designs used for metallic heat wheels: metallic mesh and corrugated panels. The mesh units have no uniform flow paths and, as a result, the gas flow through the mesh is random. This random flow path is well suited for clean flue gas because the heat transfer from the gas to the mesh is good, but under dirty conditions the mesh tends to become clogged with particles. In order to overcome this problem, corrugated metal units are used where there are relatively straight flow passages, which makes it more difficult for the particulates to clog the passages.

Metallic heat wheels have been built in a variety of sizes; the largest has 21m (70 ft) diameter wheels. Manufacturers report installations with firing rates ranging from 10 to nearly 800 GJ/hr. The design effectiveness* of such units is very high, typically in the range of 70 to 80 percent. Metallic units are limited to low flue gas temperatures, usually in the range of 370 to 590°C, and they can preheat air to between 150 and 480°C.

The primary problem in handling high flue gas temperatures with metallic heat wheels is their size change due to thermal expansion. They also tend to warp when subjected to the thermal stresses created by the cyclical heating and cooling of the disk. To allow for disk expansion, the seals used to separate the air and gas flows are not tight. This results in leakage between the air and flue gas flows which reduces the air preheat temperature achieved. Warping can be severe enough to affect the disk rotation or cause massive leakage between the air and flue gas. Metallic units generally are not used at high flue gas temperatures.

Ceramic heat wheels solve, to a large extent, the problems of warpage and expansion because the ceramics generally have a lower thermal expansion coefficient than metals. Thermal Transfer, Inc., for example, uses a magnesia aluminasilicate ceramic. Ceramic units can be used at temperatures as high as 820°C. These units have an efficiency of up to 80 percent and can achieve an air preheat temperature of 590°C.

The disk itself has a honeycomb structure where there are well defined passages through which the air and gas flow (Figure 35). The size of the ceramic disks ranges from 0.7 to 1.8 meters in diameter and the disks have a

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* Effectiveness is the ratio of the enthalpy of the flue gas transferred (to the combustion air by the heat exchanger) to the enthalpy transferable at the thermodynamic limit.

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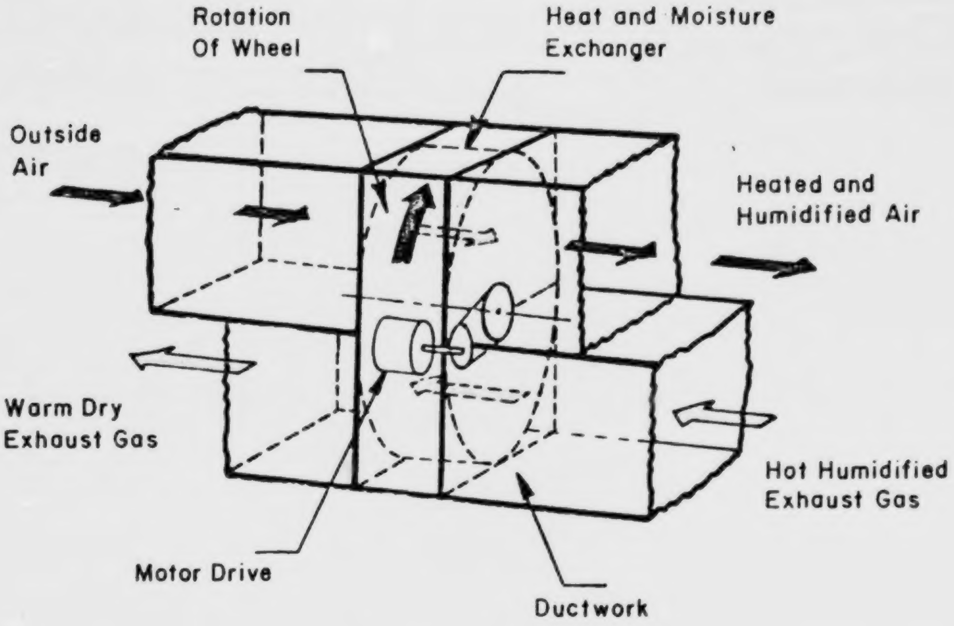
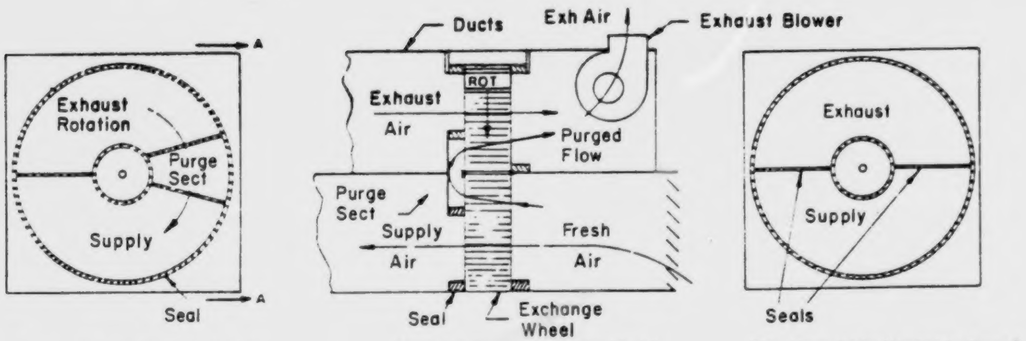

Rotation Of Wheel
Heat and Moisture Exchanger
Outside Air
Heated and Humidified Air
Warm Dry Exhaust Gas
Hot Humidified Exhaust Gas
Motor Drive
Ductwork

a) Heat wheel flow pattern.


A
A
Exhaust Rotation
Purge Sect
Supply
Seal
Ducts
Exh Air
Exhaust Blower
ROT
Exhaust Air
Purged Flow
Purge Sect
Supply Air
Fresh Air
Seal
Exchange Wheel
Exhaust
Supply
Seals

Building Side (Inside Face)
Upstream Exhaust
(Downstream Supply)

Vertical Cross Section (A-A)
Wheel, Seals and
Purge Section

Weather Side (Outside Face)
Downstream Exhaust
(Upstream Supply)

b) Heat wheel equipped with purge section to clear contaminants from the heat transfer surface.

Figure 34. Heat wheel.

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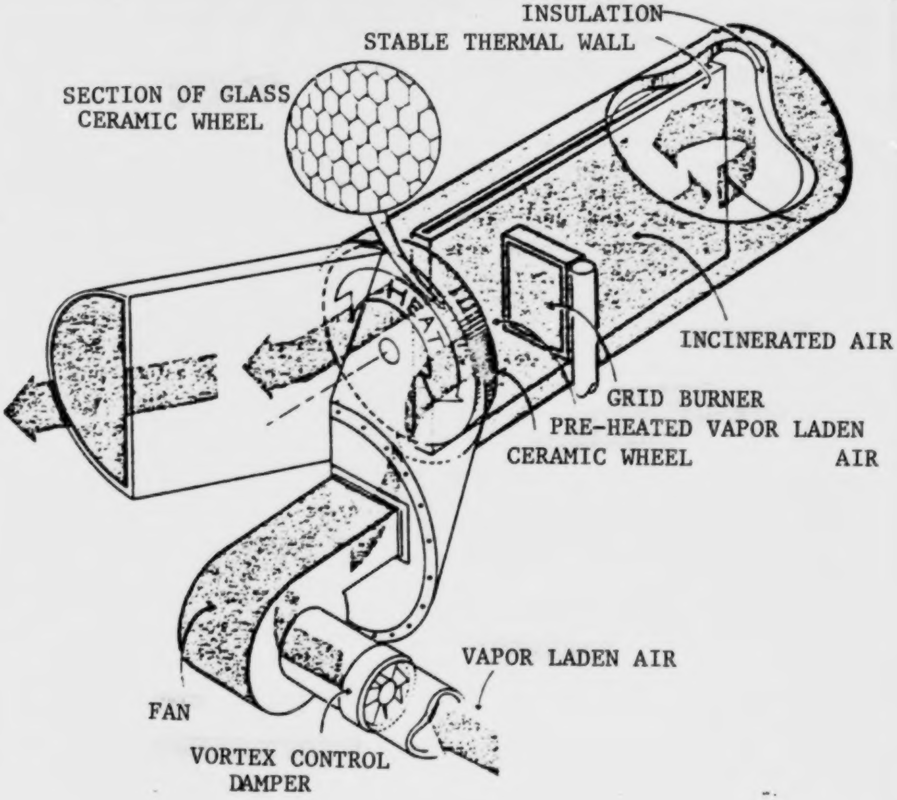
INSULATION
STABLE THERMAL WALL
SECTION OF GLASS CERAMIC WHEEL
HEAT
INCINERATED AIR
GRID BURNER
PRE-HEATED VAPOR LADEN AIR
CERAMIC WHEEL
VAPOR LADEN AIR
FAN
VORTEX CONTROL DAMPER

Figure 35. Ceramic heat wheel.

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capacity ranging up to between 60 and 100 GJ/hr. The maximum firing rate a unit can handle is determined by the unit's physical size and the air and gas temperatures.

Both metallic and ceramic units require ancillary equipment such as a drive unit, special controls, a bypass system, and a dilution air system if the application has a higher flue gas temperature than the wheel can withstand. Each system is subject to problems such as mechanical breakdown and, therefore, must be maintained carefully. Failure of a system can result in wheel damage or destruction. In addition, some systems, such as the drive unit and the dilution air system, are energy consumers resulting in additional operating expense.

### 3.3.3.2 Applications

Besides the temperature limitation of metallic and ceramic units, heat wheels are restricted to applications which do not have much particulate carry-over. Even for units with straight flow paths, such as the corrugated metallic units and the ceramic units, there is the problem of clogging under dirty conditions. The problem of fouling is reduced to some extent because the air flow over a section is in the opposite direction of the gas flow and the relatively high air and gas velocities tend to dislodge trapped particles. Ceramic units hold up quite well to corrosive agents; however, metallic units are more susceptible to corrosion, especially if the corrosive agents coat the metallic surfaces.

One of the main advantages of heat wheels is that, for the same operating conditions, they are smaller in size than a recuperator. The relatively small size of heat wheels is a result of the large heat transfer capacity per unit volume, whereas, in recuperators, there is more empty space which causes the overall unit size to be larger. Thus, heat wheels are better suited than recuperators for applications with a space limitation.

Metallic units are used on low temperature applications and can be built to handle very large volumetric capacities. Metallic heat wheels have been used on boilers, both for industrial steam generation and power plants, various furnaces such as reheat furnaces, tubestill heaters, and in the chemical processing industries.

Ceramic units have the ability to handle higher temperature flue gases than metallic units and, therefore, can attain higher preheat temperatures. Although they are limited to a flue gas inlet temperature of approximately 820°C, they can be used on higher temperature applications if a dilution air system is used. Ceramic units are less troublesome than metallic heat wheels in terms of warping and expansion, but leakage between the air and gas flows can still be a problem. Due to the size limitations, ceramic units are constrained to smaller sized furnaces, although they can be used in parallel. To date, ceramic units have been tested and used on a limited basis on a broad range of applications including steel heat treating and reheating furnaces, aluminum melting furnaces, and vapor incinerators.

### 3.3.4 Regenerators - Checkerwork

In regenerators, heat is transferred first from the flue gas to a heat storage medium such as refractory brick. The combustion air then is passed over the bricks so that the heat is absorbed by the air. The standard way to accomplish this is to have two storage media, called the refractory checker system, and to cycle the gas and air flows through each checker (Figure 36 ). While the flue gas flow is heating one checker, the air flow is being heated by the other. Typically, the cycle time (reversal time) is on the order of 15 to 30 minutes. The air temperature produced decreases through the reverse cycle as the checkerwork cools.

Regenerative systems make it possible to use flue gas temperatures and achieve preheat temperatures well above that feasible for metallic recuperators. This is because the refractory brick can withstand very high temperatures. For example, a typical glass melter will have flue gas temperatures in the range of 1430 to 1540°C and use preheated air of up to 1200°C

Traditionally, regenerators have been used widely for very high temperature applications, including melting furnaces in the glass industry, and melting furnaces and soaking pits in the steel industry. Regenerators tend to be very large and costly and thus are expensive to rebuild if they degrade. They have heat transfer rates per unit area of about one-seventh those of recuperators. The cycling air temperature is not suitable for some processes.

In many furnace systems with a regenerative system, only primary checkers are used. Primary checkers utilize very high temperature refractory brick and have large passages for the flue gas flow in order to cope with carry-overs. To design primary regenerators in cases where there is a concern about carry-over and slagging, one should have wider than usual passages and use a refractory which can withstand the chemical attack. In these cases, using a secondary checker system offers many advantages. Since carry-over is of small concern in the checkerwork, the passages can be narrower which results in a higher flowthrough velocity. The resulting higher heat transfer coefficient allows for a smaller recuperator volume to achieve the same preheat temperatures. Also, a lower-duty refractory can be utilized since the inlet temperature of the checkerwork is lower than the temperature of the primary section. An additional use of the checkerwork is to achieve a higher preheat temperature for an expensive primary regenerator.

The Morgan-Isley system is an example of a checkerwork. This system has both secondary refractories totally enclosed in a metal skin so as to prevent leakage (Figure 37 ). To control the air and gas flow, a reversing valve is utilized which also controls the flue gas ejector system. The ejector system creates a positive draft by introducing a high velocity air flow at the top of the stack. As it enters the secondary checkers, the flue gas temperature typically is in the range of 980 to 1090°C. The total regenerator system is capable of achieving preheat temperatures of approximately 1090°C at a cheaper total system cost than a primary system.

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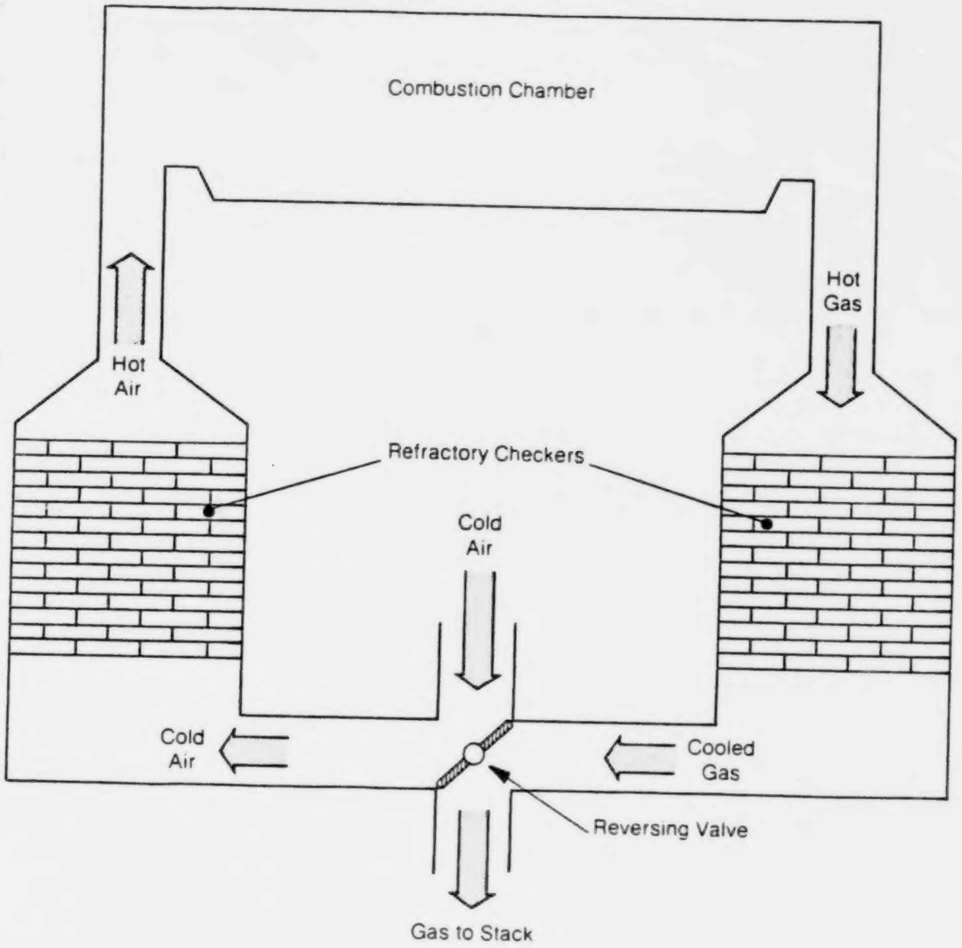
Combustion Chamber
Hot Air
Hot Gas
Refractory Checkers
Cold Air
Cold Air
Cooled Gas
Reversing Valve
Gas to Stack

Figure 36. Flow pattern in regenerators.

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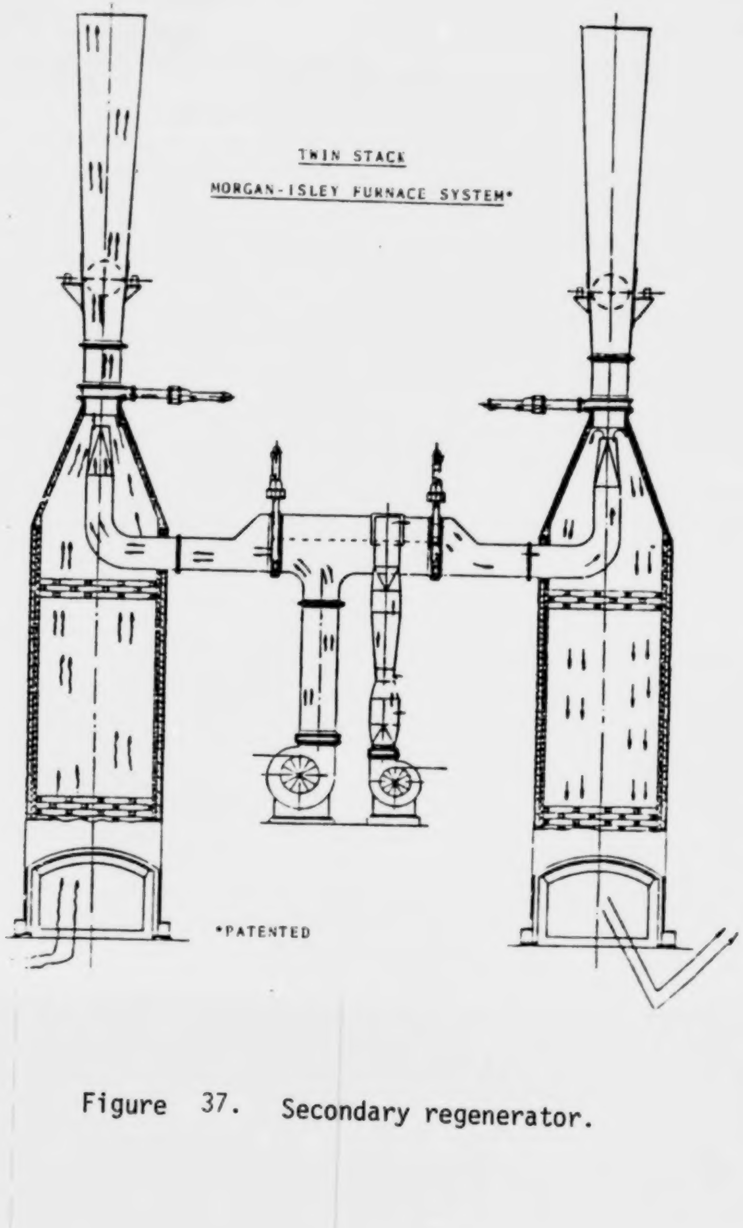
TWIN STACK
MORGAN-ISLEY FURNACE SYSTEM*
*PATENTED

Figure 37. Secondary regenerator.

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### 3.3.5 Heat Recovery Equipment for Boilers

#### 3.3.5.1 General Characteristics

Economizers and air preheaters are the two most commonly used flue gas heat recovery devices on boilers. The temperature at which the flue gases exit the steam generating section is dependent on many factors. The saturation temperature of the steam being generated and the design of the heat transfer sections are critical to determining flue gas temperatures, which usually vary from 370 to 540°C (700 to 1000°F).

An economizer is a gas-to-liquid heat exchanger. It removes heat from the flue gases and transfers heat to the feedwater, delivering it at a higher temperature to the boiler. An economizer is a convection heat transfer device. An air preheater is a gas-to-gas heat exchanger where heat removed from the exiting flue gases is transferred to the incoming combustion air. The fuels commonly burned in boilers are natural gas, fuel oils, coals, black-liquor, wood and bark, and internally generated gases such as blast furnace gas and coke oven gas. The resulting flue gases have different compositions and particulate loadings which necessitate different designs and materials for the heat recovery equipment.

Economizers usually are classified as (1) parallel or counterflow, according to the relative direction of gas and water flow; (2) plain tube or extended surface, according to the heat absorbing surface; (3) steaming and non-steaming, depending on thermal performance; and (4) staggered or in-line tube arrangements which could affect the heat transfer characteristics and have less draft. Air heaters usually are classified as recuperators or regenerators. The heat transfer mode to and from the metal/solid surface in both types is convection. Tubular or plate heaters belong to the recuperative category where the metal parts are stationary and form a boundary between the heat exchanging fluids with heat passing by conduction through the metal wall. In the rotary regenerative air heater, the heat transforming members are moved alternately through the flue gas and air streams, undergoing successive heating and cooling cycles, and transferring heat by the thermal storage capacity of the members. The air heaters may be arranged either vertically or horizontally and for either parallel or counterflows of the gas and air. No single configuration of economizers/air heaters is best suited for all applications. The selection would depend on many site-specific factors including space availability, corrosion considerations, and the amount of heat to be recovered.

Generally, boiler efficiency measures about 2.5 percent for each 56°C (100°F) drop in exit flue gas temperature. This percentage corresponds to the heat transferred to the feedwater or combustion air as a percentage of the heat input to the boiler. This efficiency indicator is useful in calculating the fuel savings associated with the heat recovery equipment.

#### 3.3.5.2 Equipment Selection and Applications

In retrofit applications, for a given amount of heat recovery, an economizer is preferred to an air heater installation. The preference is based on both technical and economic issues.

The major considerations for equipment selection and application are:

- To recover the same energy (GJ/hr), the surface area required for an air heater is larger than that for an economizer. This is primarily due to the difference in specific temperatures of the heat absorbing fluids, such as feedwater and air. This causes the air heater to be more expensive and bulky.

- The installation costs of an air heater typically are greater than that for an economizer. Besides the additional costs due to greater weight and volume, the installation requires additional direct work and vertex dampers. This could increase the cost substantially. There also may be need for a forced draft fan to blow the air through the air heater into the combustion chamber, depending on the status of the existing boiler.

- Operationally, an economizer is easier to control than an air heater. The preheated air affects fuel combustion and temperature variability due to turndown, or ambient temperature would affect the combustion efficiency. Variation in feedwater temperature is carried out easily in the steam drum.

- The existing burner would need to be replaced if it is not designed to handle preheated air. Boilers equipped with stoker firing usually cannot handle air preheated to temperatures greater than 180°C In pulverized coal-fired units, preheated air is very desirable. Dry pulverized coal units usually are equipped with air heaters that provide hot primary air to the pulverizing mills to aid pulverization.

- It has been reported that the rate of nitrogen oxide formation is experimentally dependent on temperature and is a function of the degree of combustion air preheating. This subject is discussed in Chapter 6.

### 3.3.5.3 Heat Transfer

Economizers are recuperative heat exchangers which transfer heat from the flue gases to the incoming feedwater. One fluid is separated from the other by the tube wall through which the heat flows. Figure 38 shows the thermal circuit for heat flow from the hot flue gas through the metal wall to the feedwater.

Convection and conduction are the predominant heat transfer mechanisms of an economizer. Heat is transferred from the hot gas to the outer wall surface of the feedwater tube by the convective mode. (When the temperatures are relatively high, the radiation mode may be acting in parallel.) The heat flow through the wall may be referenced as:

$$q = h_{c1} A_1 (T_g - T_{sg}) \text{ or } q = \frac{A_1 (T_g - T_{sg})}{R_1} \quad (5)$$

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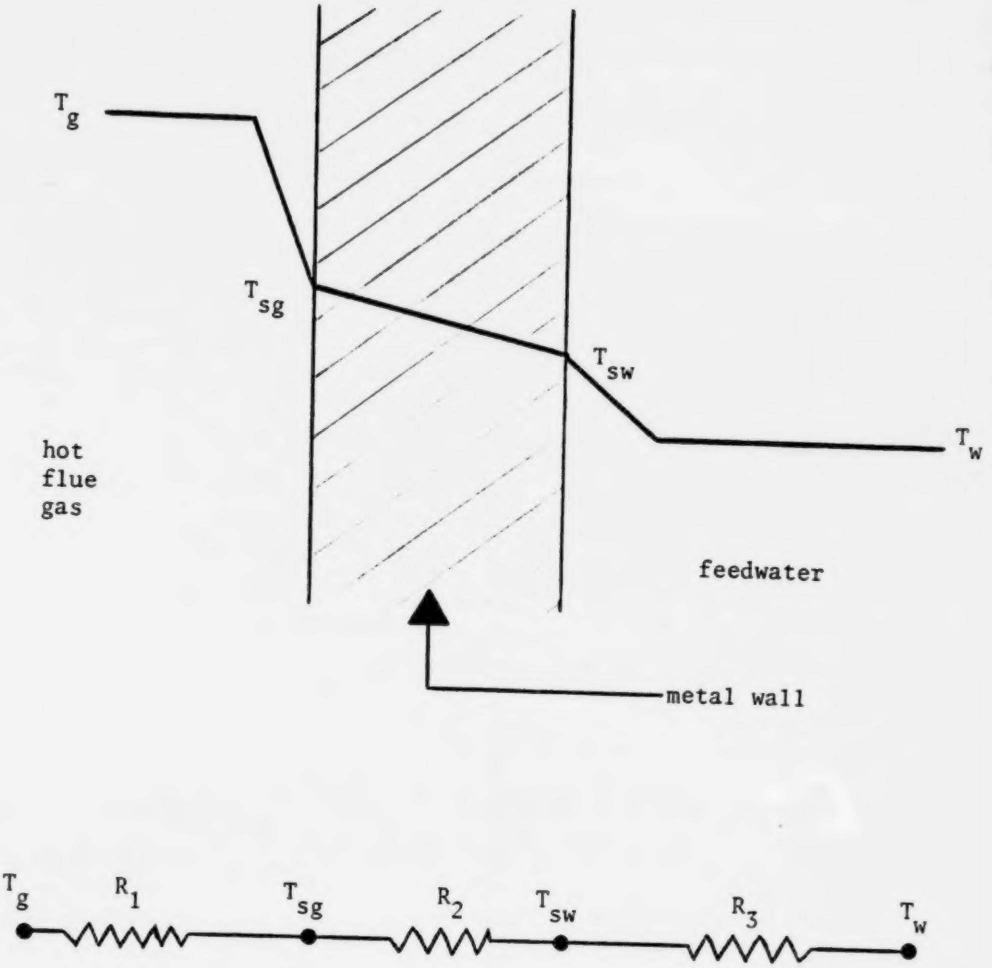
$T_g$
$T_{sg}$
$T_{sw}$
$T_w$
hot flue gas
feedwater
metal wall
$T_g$
$R_1$
$T_{sg}$
$R_2$
$T_{sw}$
$R_3$
$T_w$

Figure 38. Heat transfer.

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where $q$ = rate of heat flow

$h_{c1}$ = convective heat transfer coefficient

$A_1$ = area available for heat transfer

$T_g$ = temperature of the flue gas

$T_{sg}$ = temperature of flue gas at the outer wall

$R_1 = 1/h_{c1}$ = effective thermal resistance of first section

In steady state, heat is conducted through the metal wall at the same rate; therefore:

$$q = q_k = \frac{kA_2}{L} (T_{sg} - T_{sw}) \tag{6}$$

$$q = \frac{A_2 (T_{sg} - T_{sw})}{R_2}$$

where $q_k$ = rate of heat flow by conduction

$k$ = thermal conductivity of the metal

$A_2$ = area through which heat flows by conduction to be measured perpendicular to the direction of heat flow

$L$ = thickness of metal wall (tube)

$T_{sw}$ = temperature of water at the inner wall of the tube

$R_2 = L/K$ = thermal resistance of second section

After passing through the wall, the heat flows through the system's third section by convection to the feedwater. The rate of heat flow in this step is:

$$q = q_c = h_{c3}A_3 (T_{sw} - T_w) \tag{7}$$

$$q = \frac{A_3 (T_{sw} - T_w)}{R_3}$$

where $h_{c3}$ = convective heat transfer coefficient

$T_w$ = temperature of the feedwater

$R_3 = 1/h_{c3}$ = thermal resistance of the third section

$A_3$ = area available for heat transfer

The total thermal resistance in the system is a summation of the thermal resistance of the three sections (resistance in series):

$$R = R_1 + R_2 + R_3 \qquad (8)$$

where $R$ = total thermal resistance

The overall units conductance $\bar{U}$ is, therefore, $\bar{U} = 1/R$.

For the purpose of changing an economizer, the thermal resistances in the three sections need to be calculated. The thermal resistances for the forced convection mode ($R_1$ and $R_3$) are impacted by many parameters, such as third flow, temperature, and heat transfer characteristics. The correlation of heat transfer data with flow phenomena is accomplished most satisfactorily by the use of dimensionless numbers. The Reynolds number is a criterion for similarity in fluid flow through pipes and represents the ratio of inertial forces to viscous forces. The Prandtl number serves similarly as a criterion of temperature gradient and is a ratio of specific heat to the fraction of thermal conductivity and viscosity. The physical meaning of the Nusselt number is that it is the ratio of two temperature gradients: (1) the temperature gradient at the wall, and (2) the average temperature gradient across the entire pipe. The Stanton number is a ratio of heat absorbed to that available for absorption. The Nusselt number can be expressed as a product of the Stanton, Reynolds, and Prandtl numbers. The thermal resistance for section 2 ($R_2$) is relatively easy to calculate given the material and tube thickness. The total rate of heat flow q is expressed in the equation below:

$$q = \bar{U}\,A\Delta T \qquad (9)$$

where $\Delta T$ = mean temperature difference

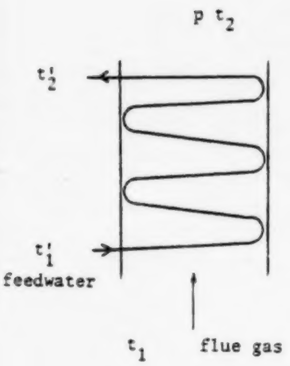
$A$ = function of $A_1$, $A_2$, $A_3$

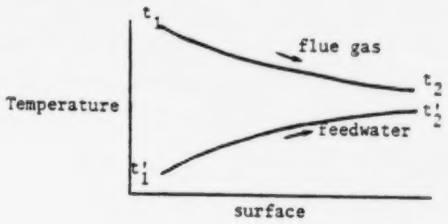
$\bar{U}$ = overall unit conductant $= \dfrac{1}{R_1 + R_2 + R_3}$

## Mean Temperature Difference (ΔT)

The temperature of fluids in a heat exchanger generally are not constant, but vary from point to point as heat flows from the hotter to the colder fluid. Therefore, the rate of heat flow varies depending on temperature differences between the hot and cold fluid. The profile of the flue gas temperatures and the feedwater in the economizer depends on their relative flows. The three general arrangements are parallel flow, counterflow, and crossflow. Assuming a one pass system, Figure 39 diagrammatically shows the flow arrangements and the respective mean temperature differences. In equation 9, if q, the heat transfer rate (GJ/hr), and ΔT, the mean temperature difference, (°C), are specified, the product of overall conductance ($\bar{U}$) and the heat transfer area (A) is readily calculable. Site-specific conditions would specify the economizer design; this, in turn, would affect the magnitude of the overall conductance and, thus, the surface area necessary for the heat transfer can be calculated.

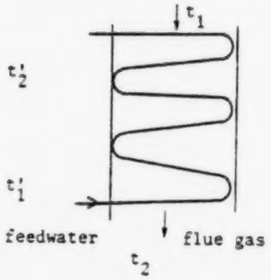
Parallel Flow

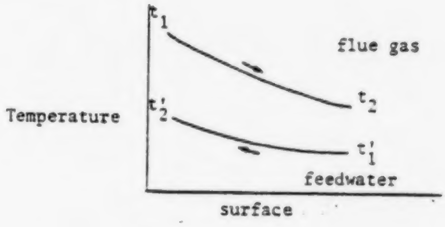

p $t_2$
$t_2'$
$t_1'$
feedwater
$t_1$
flue gas



$$\Delta T = \frac{(t_1 - t_1') - (t_2 - t_2')}{\log_e\left(\frac{t_1 - t_1'}{t_2 - t_2'}\right)}$$

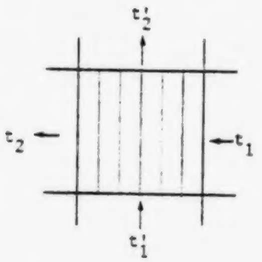
Counter Flow

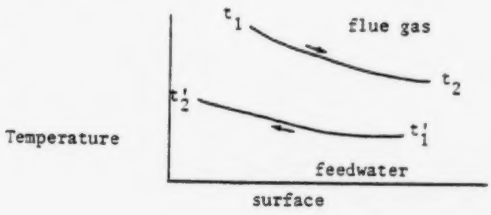

$t_1$
$t_2'$
$t_1'$
feedwater
flue gas
$t_2$



$$\Delta T = \frac{(t_1 - t_2') - (t_2 - t_1')}{\log_e\left(\frac{t_1 - t_2'}{t_2 - t_1'}\right)}$$

Cross Flow





$$\Delta T = \frac{(t_1 - t_2') - (t_2 - t_1')}{\log_e\left(\frac{t_1 - t_2'}{t_2 - t_1'}\right)} \times Fc$$

Fc = crossflow convection factor $(0 \le Fc \le 1)$

Figure 39. Flow patterns and temperature differences.

### 3.3.5.4 Material Selection and Design

An economizer is subject to both external and internal corrosion. External corrosion may occur from conduction of sulfuric acid on the outside of the tubes. Internal corrosion may occur from dissolved oxygen and low hydroxyl ion concentrations (low pH) in the feedwater on the inside of the tubes. Therefore, selecting a suitable material is important in economizer design.

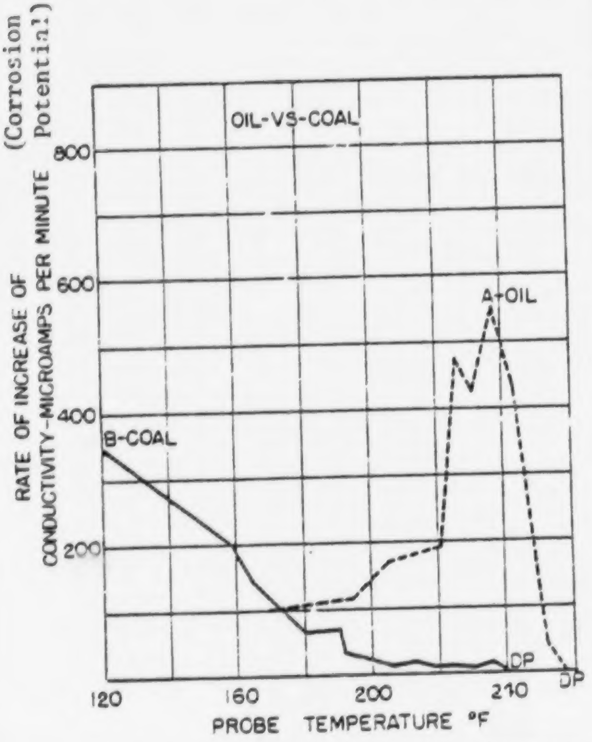
The prime cause of external corrosion and fouling is the condensation of sulfuric acid on low temperature heat transfer surfaces. The rate of acid condensation depends on several factors including sulfur content of the fuel, moisture content, boiler load, fuel mixtures, and excess air. The corrosion potential of the gases has been measured by many investigators and the test results were reviewed by Norman Clark.[37] Figure 40 shows typical curves of corrosion and fouling potential for both oil- and coal-firing. The vertical scale designates the rate of acid condensation. The horizontal scale is the temperature of the metal tube. The DP noted on the graph is the acid dew point temperature. Corrosion potential below 100 is minimal and normally does not require use of special materials. With potentials greater than 100, corrosion occurs rapidly and corrosion resistant material is required.

Internal corrosion is caused by dissolved oxygen and low pH in the feedwater. Oxygen corrosion can be controlled by deactivation at or above 100°C. Steel in the economizer is attacked by acid water and pure water; therefore, it is necessary to maintain a pH value between eight and nine. As a result, water pretreatment can be used to prevent material corrosion.

Vendors use many materials to construct economizers. The materials commonly used are carbon steel, corrosion resistant low alloy steels, stainless steel, cast iron, and porcelain enameled steel. Depending on the application, vendors also may use nickel-based alloys such as Inconel, copper-based alloys such as Cupronickel, and iron-based alloys such as Ehrite (26% Cu, 1% Ni). Figure 41 presents the suggested minimum average cold end temperature for different fuels with varying sulfur content and the materials that may be used to combat external corrosion. To prevent external corrosion, the economizer may be designed to operate at temperatures above the dew point, a bypass arrangement may be installed to provide heat to the cold end at a critical temperature, or the cold end of the economizer may be constructed with corrosion resistant alloys or porcelain enameled steel. The optimal configuration would depend on the benefit/cost ratio of the competing configurations.

Most economizers are designed for a particular application. The economizer shape and size depend on site-specific factors, such as where the economizer is expected to be located (stack, breeching), how many boilers it will service, the economizer duty (GJ/hr), and the fuel type being fired.

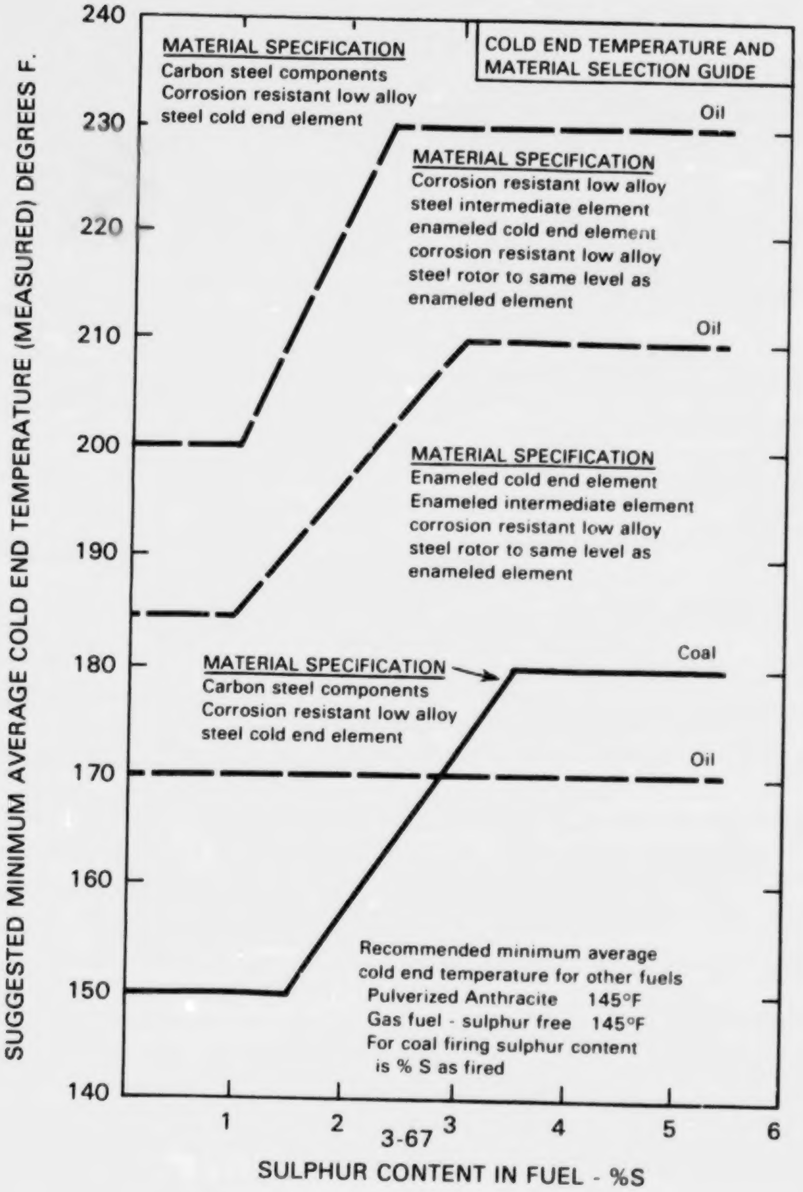
The economizer duty is the amount of heat per unit of time that is expected to be transferred to the feedwater by the economizer. For the same heat input to the boiler, coal usually generates a larger mass flow rate of flue gas than does gas or oil. But, because of the particulate loading in the flue gas, the heat transfer area for the same economizer duty is larger be-



— Comparison of condensation rates and temperature for an oil and a coal-fired boiler. (A) Oil-fired boiler. (B) Coal-fired boiler.

T (°C) = (T (°F)-32)/1.8
Source: Reference 3

Figure 40. Corrosion and fouling potential in boilers.



Note: T (°C) = (T(°F)-32)/1.8

Figure 41. Cold end temperature and material selection guide.

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cause the heat exchanger tube's arc is likely to have widely spread fins. These factors make a coal-fired boiler economizer larger than a gas or oil-fired one.

It is preferable for boiler flue gas to flow down across the economizer tubes and for the water to enter at the bottom and flow up through the tubes. This counterflow design reduces both the surface and draft ion to a minimum and provides a greater mean temperature difference. The upflow of water eliminates unstable water flow. In some cases, the location of the exonomizer in an upward flowing gas stream is fixed by the layout. In such cases, economizers can be installed for a parallel flow. The flow arrangement minimizes the potential for cold end corrosion. Given a number of design parameters discussed in the heat transfer section (3.3.5.3), the area necessary for heat transfer can be calculated using equation 10. To help efficiently transfer heat to the feedwater, fins commonly are used. The number of fins per cm of one tube depends on the fuel type. The fin count for gas is usually 2 to 3. Coal-fired boilers would use bare tubes of ≲1/cm(1-2/in) on the economizer. This prevents ash accumulation on the tubes and facilitates the use of sootblowers. The contribution of the fin area to the surface area necessary for heat transfer is given by the formula:

$$\text{surface area per inch} = \frac{\pi}{12} \cdot n \cdot \frac{(DF^2 - DT^2 + TF * DF)}{2} \qquad (10)$$

$n$ = fin count, number of fins per cm

$DF$ = outer diameter of fin, cm

$DT$ = outer diameter of tube, cm

$TF$ = fin thickness, cm

Given the area necessary for total heat transfer and the total area available per unit length, the total length of the finned tube can be calculated. This helps determine the physical size of the economizer.

### 3.3.5.5 Cost of Economizers

The equipment cost of economizers is determined largely by the heat transfer area required to transfer a given heat quantity. The larger the economizer duty, the larger is the heat transfer area and the equipment cost. The surface area, for a given economizer duty, varies with different fuels. For example, coal-fired boilers require larger economizers than gas-fired boilers with the same heat input. The cost per unit area of the heat transfer surface depends on the construction material and the economizer duty. With increasing economizer duty, the cost per unit area of the materials decreases, primarily reflecting economies of scale. Conversations with vendors indicated that a floor exists on the cost of materials per unit area. Cost variance of economizer equipment among vendors can be expected because of different "standard" equipment. Most vendors' equipment costs include the casing, tubing, insulation, and inlet/outlet transitions. Sootblowers could be installed on request. The number and type of sootblowers would depend on the economizer size. A three-way bypass arrangement and a temperature recording device sometimes are used for cold end corrosion control. The costs normally are quoted Freight on Board (FOB) vendor's plant.

Great variability exists in the costs of installing these units. Distance from the plant can cause variations in transportation costs. The largest variations occur because of site-specific factors, such as space limitations, strength of the existing structure, decision to install the economizer in the breeching versus the stack, and the foundation work, plumbing, and ductwork that accompanies the installation. Vendors indicated that the installation cost alone could vary between half the cost and twice the cost of the economizer equipment.

Economizers usually are installed when the boiler is shut down for annual maintenance. The installation could take between one and four days to complete, depending on the size of the economizer and the complexity of the installation. No "downtime" economic penalty was added to the total cost of the economizer because the installation did not affect business adversely.

Economizer installation normally does not increase the annual operation and maintenance costs of the boiler. The sootblowers usually are operated once a shift and the process is not labor intensive. The amount of steam used in sootblowing is not a significant cost. Economizer vendors indicated that usually no additional self-induced/forced draft fans are required. The existing fans can handle the additional 5cm water drop that may occur on installation of an economizer. The increased electric power costs are not significant and the maintenance required on these units is not extensive.

Table 27 presents the generic installed costs of economizers in 1979 dollars on gas/oil-fired boilers. The equipment includes the casing, tubes, insulation, and inlet/outlet transitions. Installation costs have been assumed to be 100 percent of the equipment costs, since installed costs are considered a summation of equipment costs and installation costs. The costs have been shown for different heat inputs to the boiler, and varying flue gases are fixed at 150°C. This temperature was chosen to prevent external cold end corrosion of carbon steel tubes.

Table 28 presents the generic installed costs of economizers in 1979 dollars on coal-fired boilers (stoker and pulverized coal). In addition to the standard economizer, bypass arrangement and temperature control for corrosion control and sootblowers are included. The assumptions for installation costs and flue gas temperatures for gas/oil-fired boilers also apply for coal-fired boilers.

### 3.3.6 Heat Recovery Equipment for Tubestill Heaters

Petroleum refining, one of the most energy-intensive industries in the U.S., consumes in excess of 3 EJ (3 quads) of energy per year. Over 50 percent of this energy is utilized as process heat from fuel combustion in refinery process furnaces. In previous years, with inexpensive natural gas and fuel oil available for combustion, it was not prudent to spend capital to build these furnaces for maximum fuel economy. In most cases, from 25 to 35 percent of the heat was lost in the flue gases leaving the furnace chimney.

## TABLE 27 ECONOMIC COSTS FOR GAS/OIL COMBUSTION - INSTALLED 1979 DOLLARS; T OUT = 150°C (300°F)

| | | Flue Gas Temperature °F | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 350 | | 400 | | 450 | | 500 | | 550 | | 600 | | 650 | | 700 | |
| Mass Flow of Comb. Prods.* | Firing Rate** | Btu Avail | Cost+ | Btu Avail. | Cost | Btu Avail | Cost | Btu Avail | Cost | Btu Avail | Cost | Btu Avail | Cost | Btu Avail | Cost | Btu Avail | Cost |
| 9019 | 10 | 0.13 | 5028 | 0.25 | 7281 | 0.38 | 8839 | 0.51 | 10031 | 0.63 | 10994 | 0.76 | 11801 | 0.88 | 12495 | 1.01 | 13101 |
| 27059 | 30 | 0.38 | 10555 | 0.76 | 15284 | 1.14 | 18555 | 1.52 | 21058 | 1.89 | 23080 | 2.27 | 24774 | 2.65 | 26229 | 3.03 | 27503 |
| 45099 | 50 | 0.63 | 14901 | 1.26 | 21577 | 1.89 | 26195 | 2.53 | 29728 | 3.16 | 32583 | 3.79 | 34975 | 4.42 | 37029 | 5.05 | 38826 |
| 63140 | 70 | 0.88 | 18701 | 1.77 | 27079 | 2.65 | 32874 | 3.54 | 37308 | 4.42 | 40891 | 5.30 | 43893 | 6.19 | 46471 | 7.07 | 48726 |
| 81179 | 90 | 1.11 | 22158 | 2.27 | 32086 | 3.41 | 38952 | 4.55 | 44205 | 5.68 | 48451 | 6.82 | 52007 | 7.96 | 55062 | 9.09 | 57735 |
| 99919 | 110 | 1.39 | 25372 | 2.78 | 36740 | 4.17 | 44602 | 5.56 | 50617 | 6.95 | 55479 | 8.33 | 59551 | 9.72 | 63049 | 11.11 | 66110 |
| 117259 | 130 | 1.64 | 28401 | 3.28 | 41125 | 4.92 | 49926 | 6.57 | 56659 | 8.21 | 62102 | 9.85 | 66660 | 11.49 | 70575 | 13.13 | 75331 |
| 135299 | 150 | 1.89 | 31281 | 3.79 | 45296 | 5.68 | 54989 | 7.58 | 62405 | 9.47 | 68399 | 11.37 | 74457 | 13.26 | 81026 | 15.15 | 86921 |
| 153339 | 170 | 2.15 | 24039 | 4.29 | 49289 | 6.44 | 59837 | 8.59 | 67907 | 10.73 | 75979 | 12.88 | 84385 | 15.03 | 91829 | 17.17 | 98510 |
| 171379 | 190 | 2.40 | 26693 | 4.80 | 53132 | 7.20 | 64502 | 9.60 | 74128 | 12.00 | 84917 | 14.40 | 94312 | 16.80 | 102633 | 19.19 | 110100 |
| 189419 | 210 | 2.65 | 29257 | 5.30 | 56846 | 7.96 | 69010 | 10.61 | 81931 | 13.26 | 93056 | 15.91 | 104240 | 18.56 | 113436 | 21.22 | 121689 |
| 207460 | 230 | 2.90 | 41743 | 5.81 | 60446 | 8.71 | 74398 | 11.62 | 89735 | 14.52 | 102795 | 17.43 | 114168 | 20.33 | 124240 | 23.24 | 133279 |
| 225500 | 250 | 3.16 | 44160 | 6.31 | 63945 | 9.47 | 80868 | 12.63 | 97538 | 15.78 | 111733 | 18.94 | 124095 | 22.10 | 135044 | 25.26 | 144868 |
| 243540 | 270 | 3.41 | 46515 | 6.82 | 67355 | 10.23 | 87337 | 13.64 | 105341 | 17.05 | 120672 | 20.46 | 134023 | 23.87 | 145847 | 27.28 | 156458 |
| 261580 | 290 | 3.66 | 48813 | 7.32 | 70684 | 10.99 | 93806 | 14.65 | 113144 | 18.31 | 129611 | 21.97 | 143951 | 25.63 | 156650 | 29.30 | 168047 |
| 279620 | 310 | 3.91 | 51061 | 7.83 | 75237 | 11.74 | 100276 | 15.66 | 120947 | 19.57 | 138549 | 23.49 | 153878 | 27.40 | 167454 | 31.32 | 179637 |
| 297659 | 330 | 4.17 | 53262 | 8.33 | 80091 | 12.50 | 106745 | 16.67 | 128750 | 20.84 | 147488 | 25.00 | 163806 | 29.17 | 178257 | 33.34 | 191226 |
| 315699 | 350 | 4.42 | 55420 | 8.84 | 84945 | 13.26 | 113215 | 17.68 | 136552 | 22.10 | 156427 | 26.52 | 173733 | 30.94 | 189061 | 35.36 | 202815 |

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*lbs/hr
**MMBtu/hr
+Dollars

Note: T (°C) = (T(°F) - 32)/1.8
E (joules) = E (Btu) x 1055
M (kg) = M (lb) x 0.454

Excess Air 15%

## TABLE 28. ECONOMIC COSTS FOR COAL COMBUSTION*
## INSTALLED 1979 DOLLARS; T OUT = 150°C (300°F)

| | | Flue Gas Temperature °F | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 350 | | 400 | | 450 | | 500 | | 550 | | 600 | | 650 | | 700 | |
| Mass Flow of Comb. Prods.** | Firing Rate+ | Btu Avail | Cost++ | Btu Avail | Cost | Btu Avail | Cost | Btu Avail | Cost | Btu Avail | Cost | Btu Avail | Cost | Btu Avail | Cost | Btu Avail | Cost |
| 10577 | 10 | 0.15 | 8248 | 0.30 | 11455 | 0.44 | 13690 | 0.59 | 15409 | 0.74 | 16803 | 0.89 | 17973 | 1.04 | 18980 | 1.18 | 19863 |
| 31733 | 30 | 0.44 | 15996 | 0.89 | 22728 | 1.33 | 27429 | 1.78 | 31028 | 2.22 | 33954 | 2.67 | 36411 | 3.11 | 38525 | 3.55 | 40378 |
| 52889 | 50 | 0.74 | 22088 | 1.48 | 31592 | 2.22 | 38216 | 2.96 | 43309 | 3.70 | 47440 | 4.44 | 50909 | 5.18 | 53893 | 5.92 | 56509 |
| 74045 | 70 | 1.04 | 27414 | 2.07 | 39341 | 3.11 | 47654 | 4.15 | 54046 | 5.18 | 59231 | 6.22 | 63583 | 7.26 | 67329 | 8.29 | 70612 |
| 95201 | 90 | 1.33 | 32260 | 2.67 | 46392 | 4.00 | 56243 | 5.33 | 63817 | 6.66 | 69959 | 8.00 | 75516 | 9.33 | 82220 | 10.66 | 88249 |
| 116357 | 110 | 1.63 | 36766 | 3.26 | 59125 | 5.78 | 71750 | 6.52 | 72899 | 8.15 | 82801 | 9.77 | 92030 | 11.40 | 100225 | 13.03 | 107594 |
| 137513 | 130 | 1.93 | 41011 | 3.85 | 59125 | 5.78 | 71750 | 7.70 | 85153 | 9.63 | 97637 | 11.55 | 108545 | 13.48 | 118230 | 15.40 | 126938 |
| 158669 | 150 | 2.22 | 45049 | 4.44 | 64999 | 6.66 | 81227 | 8.89 | 98069 | 11.11 | 112474 | 13.35 | 125060 | 15.55 | 136234 | 17.77 | 146282 |
| 179825 | 170 | 2.52 | 48914 | 5.04 | 70625 | 7.55 | 91890 | 10.07 | 110985 | 12.59 | 127311 | 15.11 | 141574 | 17.62 | 154239 | 20.14 | 165627 |
| 200981 | 190 | 2.81 | 52634 | 5.63 | 76887 | 8.44 | 102568 | 11.25 | 123901 | 14.07 | 142147 | 16.88 | 158089 | 19.70 | 172243 | 22.51 | 184971 |
| 222137 | 210 | 3.11 | 56229 | 6.22 | 84857 | 9.33 | 113239 | 12.44 | 136817 | 15.55 | 156984 | 18.66 | 174604 | 21.77 | 190248 | 24.88 | 204316 |
| 243293 | 230 | 3.41 | 59714 | 6.81 | 92824 | 10.22 | 123909 | 13.62 | 149732 | 17.03 | 171820 | 20.44 | 191118 | 23.84 | 208253 | 27.25 | 223660 |
| 264449 | 250 | 3.70 | 63102 | 7.40 | 100791 | 11.11 | 134577 | 14.81 | 162648 | 18.51 | 186657 | 22.21 | 207633 | 25.92 | 226257 | 29.62 | 243004 |
| 285605 | 270 | 4.00 | 66405 | 8.00 | 108759 | 12.00 | 145250 | 15.99 | 175564 | 19.99 | 201494 | 23.99 | 224148 | 27.99 | 244262 | 31.99 | 262349 |
| 306761 | 290 | 4.29 | 69625 | 8.59 | 116726 | 12.88 | 155920 | 17.18 | 188480 | 21.47 | 216380 | 25.77 | 240662 | 30.06 | 262267 | 34.36 | 281693 |
| 327917 | 310 | 4.59 | 72776 | 9.18 | 124693 | 13.77 | 166590 | 18.36 | 201396 | 22.95 | 231167 | 27.55 | 257177 | 32.14 | 280271 | 36.73 | 301037 |
| 349073 | 330 | 4.89 | 76627 | 9.77 | 132661 | 14.66 | 177261 | 19.55 | 214512 | 24.44 | 246005 | 29.32 | 273692 | 34.21 | 298276 | 39.10 | 320382 |
| 370229 | 350 | 5.18 | 81178 | 10.37 | 140628 | 15.55 | 187731 | 20.73 | 227228 | 25.92 | 260840 | 31.10 | 290208 | 36.28 | 316280 | 41.47 | 359726 |

Excess Air = 20%

---

*Includes sootblowers and bypass arrangement for corrosion control
**lbs/hr
+MMBtu/hr
++Dollars

Note: $T\ (^{o}C) = (T(^{o}F) - 32)/1.8$
$E\ (\text{joules}) = E\ (\text{Btu}) \times 1055$
$M\ (\text{kg}) = M\ (\text{lb}) \times 0.454$

Of course, there has been a dramatic change in philosophy since fuel prices began to escalate in 1973. Today, new furnaces are being installed with large, expensive heat recovery devices and the refiner is expending much effort in devising means for recovering wasted energy in existing furnaces. The economics are drastically different and technology is being developed to provide optimal solutions to the conservation requirement.

The process furnace is a key equipment component in a refinery unit. Distillation, separation, cracking, and reforming all require fluid temperatures in the range of 260 to 540°C and direct radiation from fuel combustion is the most effective means for obtaining these temperatures.

A typical refinery designed for the production of gasoline, kerosene, jet fuel, No. 2 fuel oil, and No. 6 fuel oil will require approximately 20 process furnaces. For a 100,000 barrel per day crude capacity, the heat absorbed by the process fluids in these furnaces would total 1800 GJ/hr. The fuel required to affect this heat absorption could vary from 2000 to 3000 GJ/hr. depending on the magnitude of heat recovery equipment supplied with the furnaces. It is evident that heat recovery in refinery furnaces can result in sizeable energy savings.

### 3.3.6.1 General Description of Petroleum Refining Process Furnaces

The refinery furnaces consist of two major parts: (1) the radiant section, and (2) the convection section.

#### 3.3.6.1.1 Radiant Section

The radiant section is a refractory-lined chamber with tubes mounted adjacent to the walls. The heated hydrocarbon flows inside the tubes. Fuel is burned in the radiant section and the heat is radiated from the combustion products to the tubes. Heat is transmitted by conduction through the tube wall to the fluid inside the tubes. The temperature of the combustion products exiting from the radiant section is in the range of 650 to 980°C; therefore, these gases contain sizeable quantities of heat, as much as 50 percent of that released by fuel combustion.

#### 3.3.6.1.2 Convection Section

The convection section is designed to receive a portion of heat prior to the escape of the gases to the stack. The convection section usually is a bank of tubes located above the radiant section in the path of the flue gases leaving the radiant section, with process fluid flowing through the tubes. The surface area of the tubes determines the amount of heat recovery and the combustion process efficiency. The greater the tube surface, the more heat is recovered from the flue gases, but the capital investment also is higher. The fluid in the convection tubes can be the same or different than that flowing through the radiant tubes. In many cases, the convection section is utilized to generate steam for use in the process. Convection tubes can be bare or extended surface. By using fins or studs welded to the bare surface, heat transfer is improved and a smaller number of tubes is required for the same heating requirement. A finned surface is more susceptible to fouling from ash and other inert material deposits in the fuel. Means for cleaning this surface must be provided.

### 3.3.6.1.3 Furnace Types

There are two general types of refinery furnaces: (1) vertical cylinder, and (2) horizontal box. These are shown in Figure 42. Items f, g, and h are vertical cylinders and the remaining are horizontal box furnaces.

In the vertical cylinder, the radiant section is a tall, refractory-lined cylinder with vertical tubes supported from the roof and mounted in a circle near the wall. The burners are mounted on the floor and fired upward. A horizontal convection section usually is mounted on top of the furnace with the stack located above the convection section.

The horizontal box furnaces is a rectangular cross section, refractory-lined, with tubes either vertically or horizontally mounted adjacent to the walls. Burners are either on the floor for vertical firing or in the side walls for horizontal firing. A horizontal tube convection section usually is located above the radiant section.

### 3.3.6.1.4 Combustion

Fuel to the refinery furnaces can be natural gas, light distillate oil, heavy No. 6 oil, or viscous pitch. Heater designs can be arranged to accommodate a wide variety of fuels.

Natural draft generally is the technique used for supplying combustion air to the burner. A damper in the stack is adjusted manually to regulate the amount of excess air to the combustion chamber. Oxygen and $CO_2$ analyzers are used to assist the operation in the manual adjustment. The simplicity, low maintenance, and low cost of natural draft are major advantages recognized by refiners. However, there are disadvantages in that manual control of the damper usually is required and the accuracy of the setting is subject to operator error. There are some heaters with forced draft combustion, but they are rare in refineries.

The amount of excess air, as set by the damper position, is a critical factor in furnace efficiency and fuel consumption because the extra air, admitted from the atmosphere, has to be heated to firebox temperature. Some of this heat is recovered in the convection section, but much of it is lost up the stack. This is an important concept which will be considered in the discussion of air preheaters or heat recovery devices later in the report.

Table 29 is a list of furnaces in a 100,000 bbl/day refinery. The refinery was designed in 1970 and constructed in 1972. Process units include

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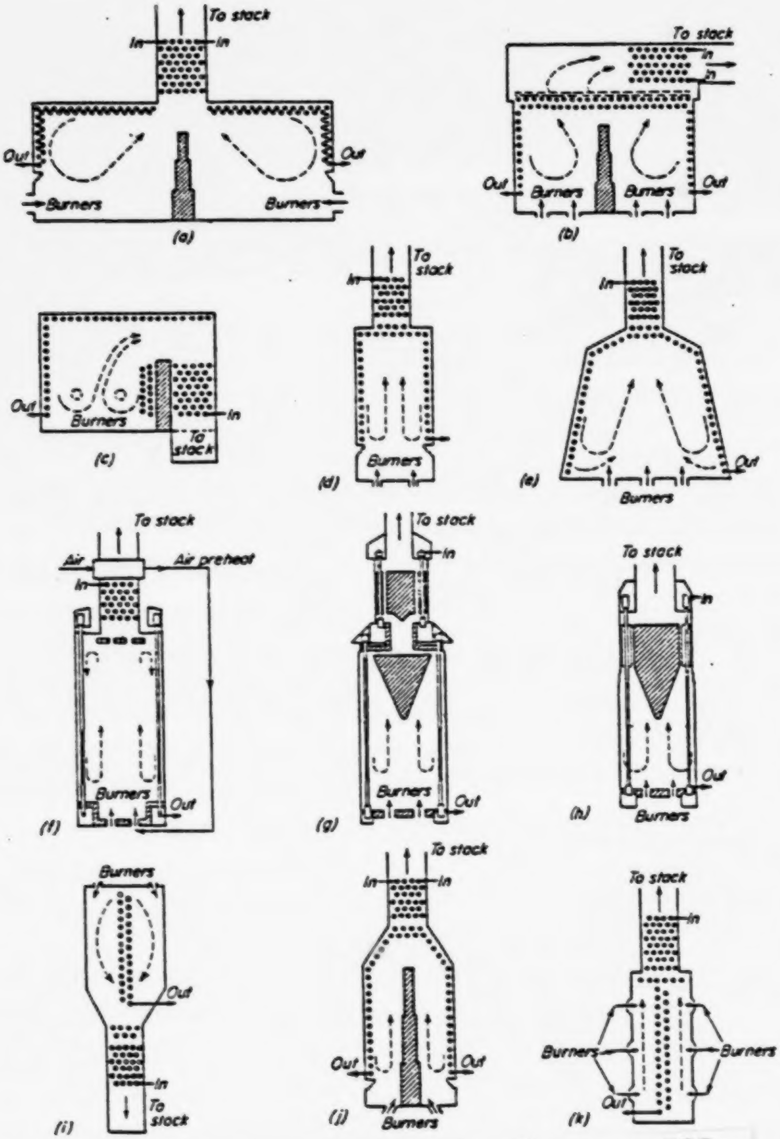
To stack
In
In
Out
Out
Burners
Burners
(a)
To stack
In
In
Out
Burners
Burners
Out
(b)
Out
Burners
In
To stack
(c)
To stack
In
Burners
(d)
To stack
In
Out
Burners
(e)
To stack
Air
Air preheat
In
Burners
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(f)
To stack
In
Burners
Out
(g)
To stack
In
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Burners
(h)
Burners
Out
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To stack
(i)
To stack
In
In
Out
Out
Burners
(j)
To stack
In
Burners
Burners
Out
(k)

SOURCE: W.L. Nelson, op. cit., p. 587.

3-77

Figure 42. Tubestill heaters and furnaces.

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3/8"
PAGE NUMBER

TABLE 29. FURNACES IN A 15,890 m$^3$/day (100,000 BBL/DAY) REFINERY

| FURNACE NUMBER | FURNACE | HEAT ABSORBED | HEAT RELEASED | FLUE GAS* TEMPERATURE | FLUE GAS FLOW |
|---|---|---|---|---|---|
| 1 | Crude | 325 | 409 | 740 | 376 |
| 2 | Vacuum | 100 | 200 | 1650 | 182 |
| 3 | Visbreaker | 75 | 152 | 1575 | 122 |
| 4 | Visbreaker-Vacuum | 40 | 78 | 1490 | 63 |
| 5 | Isomax Charge | 55 | 110 | 1550 | 66 |
| 6 | Isomax Charge | 55 | 110 | 1550 | 66 |
| 7 | Debutanizer Reboil | 140 | 190 | 1001 | 153 |
| 8 | Production Fractionator | 65 | 86 | 1097 | 73 |
| 9 | Diesel Stripper | 7 | 10 | 1137 | 10 |
| 10 | Naphtha Hydrobon Charge | 30 | 44 | 1022 | 42 |
| 11 | Naphtha Hydrobon Stripper | 25 | 32 | 984 | 31 |
| 12 | Platformer Charge | 130 | 163 | 700 | 156 |
| 13 | Platformer No. 1 Reheat | 115 | 143 | 700 | 137 |
| 14 | Platformer No. 2 Reheat | 20 | 42 | 1690 | 40 |
| 15 | Stabilizer Reboiler | 32 | 46 | 998 | 44 |
| 16 | Splitter Reboiler | 15 | 17 | 936 | 16 |
| 17 | Distillate Hydrobon Charge | 22 | 44 | 1546 | 31 |
| 18 | Diesel Stripper Charge | 9 | 12 | 1025 | 10 |
| 19 | Fractionator Reboiler | 50 | 69 | 1019 | 56 |
| 20 | $H_2$ Plant Heater | 230 | 252 | 320 | 252 |
| 21 | $H_2$ Plant Heater | 230 | 252 | 320 | 252 |
| 22 | Fuel Oil Heater | 30 | 67 | 1200 | 64 |
|  | TOTAL | 1,800 | 2,258 |  | 2,242 |

* T ($^{o}$C) = (T($^{o}$F)-32)/1.8

crude distillation, vacuum distillation, visbreaker isomax, hydrogen plant, naptha hydrobon,* distillate hydrobon, and platformer and merox treaters.**

The refinery was designed to process a high sulfur crude oil with a product state consisting primarily of gasoline, jet fuel, No. 2 fuel, and No. 6 fuel oil.

### 3.3.6.2 Types of Furnace Heat Recovery Systems

Refiners are employing two major types of heat recovery systems on their furnaces: (1) tubular convection, and (2) air preheaters. Each system has its own advantages and disadvantages depending on process conditions, fuel prices, whether retrofit or new installation, and the furnace type involved.

#### 3.3.6.2.1 Tubular Convection Sections

Tubular convection sections, as described in the preceding section, have been used for years on refinery furnaces when economically justified. In most cases, convection sections were small and only a portion of the available heat in stack gases was recovered. Refiners are utilizing convection section tubes for preheating the process fluid before it enters the radiant section or for steam generation. The selection of the particular system depends on the specific application. The following examples will illustrate this point.

##### Example 1

In a catalytic reformer unit, the fluid entering the furnace is an oil and hydrogen mixture with temperature of 400°C. If this fluid were preheated in a convection coil, the furnace stack gas temperature leaving the coil could not be lower than 450°C, since a 50°C approach is required between the fluid being cooled and that being heated. Thus, only a limited amount of heat could be recovered from the flue gas. Instead of preheat, a steam generation coil could be located in the convection section, generating steam at 1.7 MPa and 200°C With this arrangement, the flue gases will be cooled to 260°C instead of the 450°C process fluid limit in the tubes. In fact, if the steam generation section includes an economizer coil (boiler feedwater heater), an even lower flue gas exit temperature could be attained.

##### Example 2

In a crude distillation furnace, the process fluid, which is crude oil, enters the furnace at 200°C. In this case, the convection section could be used to preheat the crude oil. The stack gases from which the heat is being recovered could be cooled to as low as 260°C.

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* Hydrobon (VOP trademark for hydrodesulfurization).

** Platformer and merox are VOP brand names for a catalytic reformer and a gasoline sweetener.

Below is a summary of the advantages and disadvantages of process fluid heating versus steam generation.

Process Fluid Heating

Advantages --

- Usually lowest cost, unless coil is high alloy construction.
- Compatible with operations of furnace radiant section.
- Minimum complexity of controls.

Disadvantages --

- Heat recovery is limited by process fluid inlet temperature.
- External fouling of tubes will affect furnace operations.
- If used in a corrosive environment, expensive alloys would be required and this would result in a high installation cost.

Steam Generation

Advantages --

- No limit on heat recovery, especially if economizer coil is included in convection section.
- External fouling of tubes has little effect on process.
- Coil material usually is carbon steel which is inexpensive.

Disadvantages --

- Large numbers of auxiliaries are required, i.e., steam drum, circulating pumps, and instrumentation.
- When heater is not in service, steam supply will have to be made up from another service.
- Some states require annual inspection of steam generators, thus, necessitating yearly shutdowns.

#### 3.3.6.2.2 Air Preheaters

The second type of heat recovery device applicable to process furnaces is the air preheater. Air preheaters have been used extensively in oil burners, especially the large central station units where efficiency is extremely important. However, prior to 1973, there were very few air preheaters used on refinery process furnaces because they were difficult to justify economically.

The air preheater is a device which transfers heat from the furnace flue gas to the incoming ambient air in order to preheat the air prior to combustion. With 16 to 38°C ambient air, the flue gases can be taken down as low as 150°C for maximum heat recovery. Dew point corrosion, depending on the amount of corrosive agents in the fuel, becomes the factor which limits how low the temperature can go.

There are three types of air preheaters: (a) regenerative, (b) recuperative, and (c) indirect system.

a) Regenerative

The regenerative preheater* features a large rotating metallic core which alternately passes through the flue gas and air streams at a slow rate, thus transferring heat from one to the other. The unit has basket elements in the core which can be replaced when they are corroded. On-stream cleaning is provided as required by the service.

The system requires a forced draft fan which blows ambient air through the preheater and into the burners for use in the combustion process. An air induced draft fan is utilized to draw the flue gases from the furnace through the preheater and back into the stack. Preheaters and fans usually are located on a gradient because of their large size and weight. Ductwork is required to carry the air and flue gas streams. Most units incorporate automatic bypasses around the air preheater, so that if a fan fails or basket replacement is required, the furnace remains in operation on natural draft.

The advantages of the regenerative type are that it is a direct, efficient means for transferring heat from flue gas to air and is relatively compact. The disadvantages are that (1) forced and induced draft fans are required: this means more maintenance, lower degree of reliability, and an energy debit, since most refinery natural draft furnaces without air preheaters do not have fans; (2) the system is expensive due to mechanical equipment, extensive ductwork, and controls; and (3) fouling and corrosion could cause problems if the flue gases are cooled below their dew point.

b) Recuperators

The recuperative unit features a fixed gas-to-gas heat exchanger located in the flue gas flow before it enters the stack. The exchanger consists of many internal, extended surface elements normally constructed of cast iron. Its application in the system is similar to the regenerative unit with forced and induced draft fans handling the air and flue gas streams, respectively, through extensive ductwork.

The disadvantages are similar to those indicated for the regenerative units; however, the maintenance resulting from corrosion could be much greater than for the regenerative unit. Tubular elements near the cold end could require frequent replacement if dew point conditions are prevalent. Fouling is another major problem with the recuperative unit.

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* Regenerative is the term used in this industry. Elsewhere in the text, this has been referred to as a heat wheel.

### c) Indirect System

The indirect system uses a heat transfer fluid to pick up heat from the flue gas in a convection coil. The heat transfer fluid then flows through a second coil in the air. Pumps are required to circulate the heat transfer fluid through the coils. In addition, a forced draft fan blows the air through the coil into the combustion chamber.

The indirect system is not as popular as the regenerative or recuperative systems. Although the system incorporates less ductwork, the cost of the other equipment such as two sets of coils, pumps, drivers, and instruments is usually higher than that for other systems. In addition, coking or polymerizing the heat transfer fluid sets an upper limitation on the exchange temperature, which could prove costly.

### 3.3.6.3 Current Trends

When discussing current furnace heat recovery trends in refineries, it is necessary to differentiate between new unit design and retrofitting existing units.

### 3.3.6.3.1 New Units

The trend in new units is to design furnaces for efficiencies ranging from 85 to 92 percent, or flue gas exit temperatures of 320 to 150°C When a new furnace is designed, the purchaser includes in his specifications the cost of fuel and the investment payback period used for evaluation. The furnace designer must develop heat recovery equipment which can be justified according to those guidelines. Competitive bidding improves the chances of obtaining the optimum design. It is difficult to generalize on the type of equipment to be used because each installation is different and requires individual analysis.

If the inlet process fluid temperature is in the neighborhood of 150° to 200°C, a process preheat coil in the convection section would be the favored system with flue gas being cooled to 200 to 260°C.

Extended surface would be used as extensively as possible depending on the fuel fired. If the fuel is gas or distillate, high density fins would be used. If the fuel is heavy fuel oil, No. 6 oil, or pitch, low density fins or studs would be preferred to minimize fouling. On-stream cleaning facilities should be provided also.

If the inlet process fluid is in the 260 to 370°C range, steam generation above the process preheat coil could be considered provided the heater were large enough to justify the installation of a steam system. If not, the air preheater alternative must be considered along with the process preheat coil.

On those units where process fluid inlet temperatures are in the 370°C and higher range, steam generation or air preheating must be considered. Platformers and hydrogen plant furnaces fall into this category. Since steam usually is required in these two processes, large steam generation sections usually are on the furnaces. Boiler feedwater heating coils in the convection section above the steam generating coils can bring the flue gases down to 150 to 200°C and efficiencies in excess of 90 percent can be attained.

### 3.3.6.3.2 Existing Units

Depending on their year of purchase, most existing refinery furnaces installed prior to 1973 were designed for efficiencies of 70 to 80 percent or flue gas exit temperatures of 400 to 590°C. Since 1973, there has been considerable effort expended to increase these efficiencies to the 80 to 90 percent range. This is being accomplished with the addition of steam generation in the convection section. In addition, air preheaters have been added to some existing units.

Again, it is difficult to generalize on which alternative method should be used, but the points mentioned above for new units tend to apply here also. However, the task of retrofitting can be a difficult one because of the limitations imposed by the original furnace design and installation.

To add a convection section to an existing furnace or to expand a convection section, the following considerations must be taken into account:

- Will the existing furnace structure support the additional coil?
- Is the stack tall enough to satisfy the flue gas pressure drop through the additional coil free flow area?
- Can the furnace charge pump supply sufficient pressure to overcome the added pressure drop on the process side imposed by adding the coil?
- Can the revision be completed during the normal turnaround time for the furnace?
- Is dew point corrosion in the stack a problem that can be handled?

Adding an air preheater on an existing furnace poses the following problems:

- Is there sufficient plot area?
- Are the burners suitable for forced draft operation instead of natural draft?
- Is there electric power or steam available to drive the preheater rotor and the two fans?

### 3.3.6.4 Cost

In order to develop continuous heat recovery cost curves for petroleum refinery furnaces, information as to the type of furnace, the operating temperature, and process fuel requirements would have to be known. These are difficult questions to answer due to the number of possible furnaces and applications that exists, as indicated in Table 29. Furthermore, the type of heat recovery -- process fluid preheating, steam generation and preheating, or indirect -- can greatly influence the cost. For example, based on 1979 dollars, an air preheater added to an existing 100 GJ/hr furnace would cost approximately one million dollars. These figures are approximate because the heating location, plot arrangement, and operating conditions would have to be considered, but they illustrate the magnitude of the projects being considered.

Due to the above considerations, a continuous cost function has not been developed. Rather, two examples of installed equipment, an air preheater and a steam generating convection section, are given in detail to demonstrate typical industrial applications.

#### 3.3.6.4.1 Air Preheater

In 1970, a vertical cylindrical process furnace for reboiler service was purchased as a component of a distillate hydrotreating plant. The furnace was sized for a heat absorption rate of 88 GJ/hr with an inlet process fluid temperature of 315°C. A reasonably-sized convection section was installed with the heater with an exit flue gas temperature of 435°C and a furnace efficiency of 75 percent; thus 25 percent of the fuel burner in the furnace was lost to the stack.

In 1974, following the oil embargo when fuel prices jumped to $2/GJ the refinerly investigated adding an air preheater to the reboil furnace to reduce fuel consumption. Table 30 illustrates furnace operation without an air preheater and predicted operation with an air preheater. A fuel savings of 18 GJ/hr was realized by reducing the stack gas temperature from 435 to 150°C and transferring the heat into preheated combustion air. At a fuel cost of $2 per GJ/hr, the annual savings equal $305,000.

Debited to these savings are the following added costs for air preheater operations:

| | |
|---|---|
| Maintenance | $10,000/yr |
| Tax & Insurance | $15,000/yr |
| Fan Power | $12,000/yr |

Thus the yearly savings are $305,000 minus $37,000 operational cost resulting in a net credit of $268,000. The capital cost of the air preheater installation was estimated at $800,000 in 1974.

## TABLE 30. FURNACE OPERATION WITH AND WITHOUT AIR PREHEAT

| | With Air Preheat | Without Air Preheat |
|---|---|---|
| Furnace Duty, MMBtu/hr | 83 | 83 |
| Ambient Air Temperature, °F | 80 | 80 |
| Flue Gas Temperature to Air Preheater, °F | 815 | |
| Flue Gas Temperature to Stack, °F | 300 | 815 |
| Excess Air, % | 15 | 30 |
| Furnace Efficiency, % | 94 | 79 |
| Fuel Fired, MMBtu/hr | 88 | 105 |

Note: T (°C) = (T (°F)-32)/1.8
E (J) = E (Btu) x 1055

In 1976 the same furnace was investigated again. At this time, the refinery was projecting a fuel cost of $3/GJ by 1978, the year the project would be completed. The operating cost savings increased from $268,000/yr to $420,000/yr as a result of the fuel price increase. The capital investment was re-estimated at one million dollars.

### 3.3.6.4.2 Steam Generating Convection Section

Plans are underway to reduce the fuel consumption of the 100,000 bbl/day refinery described earlier in this report. The furnaces in the refinery are listed in Table 29. The plan under consideration is to combine the flue gas flows from all furnaces except the two hydrogen furnaces and duct the gases through a steam generating waste heat boiler into a common stack. The total stack gas flow will equal 867,000 kg/hr and the flue gas temperature entering the steam generator will be approximately 540°C allowing for a 55°C temperature drop in the long lengths of ductwork connecting the furnaces to the steam generator and stack. Steam will be generated at a pressure of 4.5 MPa and superheated to 370°C in the waste heat steam generator. Calculations shown below indicate that 80,000 kg/hr of steam will be generated with the furnace flue gas exiting from the steam generator at 320°C

#### CALCULATIONS

| | |
|---|---|
| Enthalpy Steam 4.5 MPa, 370°C | 3133 kJ/kg |
| Enthalpy Boiler Feedwater | -575 kJ/kg |
| Heat Added to Steam | 2558 kJ/kg |
| Enthalpy Furnace Flue Gas 540°C | 535 kJ/kg |
| Enthalpy Furnace Flue Gas 320°C | -302 kJ/kg |
| Heat Recovered from Flue Gas | 100 kJ/kg |

STEAM GENERATED =

$$867{,}000 \text{ kg/hr Flue Gas} \times \frac{233}{2558} = 80{,}000 \text{ kJ/hr.}$$

ENERGY RECOVERED FROM FLUE GAS =

867,000 kg/hr x 233 kJ/kg = 202 GJ/hr.

UNIT ENERGY COST =

$2.84/GJ ($3/MMBtu)

YEARLY SAVINGS =

$2.84/GJ x 202 GJ/hr x 7920 hr/yr = $4,550,000

The estimated cost, including 5.5m diameter stack, ductwork connecting all the furnaces to the stack, induced draft fans, and the waste heat steam generation, is $12 million.

A major advantage is that most of the construction work can be done while the refinery is operating. Connections to individual furnaces can be completed during normally scheduled shutdowns of the furnace. Another advantage is the postponement of capital expenditure for the purchase of another refinery boiler. The 79,830 kg/hr of steam will satisfy the refinery's demands for a number of years. Finally, with a common stack, it may be possible to burn heavier, less expensive fuels and still meet air pollution regulations in certain sections of the country.

## 3.4 CONCLUSION

There is a variety of energy conservation technologies of which combustion air preheat and heating the product being the most feasible. The five equipment types that are used frequently by industry are recuperators, regenerators, econcomizers, equipment to raise steam, and product heating for tubestill heaters. Vendors and industrial users supplied information about the various equipment types. The type which is the most applicable usually depends on site-specific design needs.

# 4. WASTE HEAT RECOVERY IN FURNACES

## 4.1 INTRODUCTION

This chapter focuses on the potential uses and limitations of waste heat recovery in industrial furnaces, ovens, and kilns. These devices, due to their high temperatures and high fuel consumption rates, are regarded as the prime candidates for the use of preheated combustion air. Unfortunately, due to the wide range of designs and uses for these devices, it is impossible to define a typical furnace or develop general cost functions. In addition, the number of major furnace types is very large so that it is an unmanageable task even to consider just the major operations and the factors which would determine the installation costs of new and retrofit heat recovery equipment.

Instead, the major factors which will affect the cost of using heat recovery equipment have been identified. They are:

- Flue gas temperature
- Mode of heat transfer
- Fuel
- Firing and Loading Cycle
- Firing Rate
- Production rate
- Pollution control equipment
- Heating objective
- Physical space requirement
- Heat recovery equipment

This list is by no means inclusive or explicit, but these factors are crucial in assessing the potential and cost of heat recovery equipment.

Information on the general characteristics of selected major furnace types also is presented. In addition, concluding sections of this chapter will discuss the limitations and considerations which affect the operation and implementation of waste heat recovery from the operator's perspective.

## 4.2 MAJOR FACTORS AFFECTING HEAT RECOVERY

### 4.2.1 Flue Gas Temperature

Flue gas temperature is the most important factor when considering waste heat recovery technologies. The higher the flue gas temperature, the greater is the incentive to invest in heat recovery devices. Usually, however, if the flue gas temperature is under 540°C recuperation is only of interest in continuous 24 hour-a-day operations. For intermittent batch operations, a 650 to 760°C flue gas temperature is a practical minimum.

In most cases, the flue gas temperature is highest at the point where the gas exits the furnace. The temperature loss between the furnace exit and the heat recovery device can be reduced in several ways: minimizing air infiltration into the flue gas stream, insulating the flue gas piping, or placing pollution control equipment downstream from heat recovery devices. In some cases, the flue gas temperature actually can be higher than the process temperature, such as in furnaces with radiant tube burners. At present, flue gas temperatures in the 700 to 820°C range are considered marginal investments, and processes with flue gas temperatures near 1100°C have had heat recovery devices for years.

### 4.2.2 Mode of Heat Transfer

High temperature industrial processes involve two major types of heat transfer: radiation and convection. In a convection furnace a high gas circulation rate through the furnace is desired. The recirculation may be created by using high excess air, flue gas recirculation, or other means to achieve a strong gas flow through the furnace chamber. If high excess air is used, the amount of flue gas will be relatively high per kJ consumed; this means larger, more expensive heat recovery equipment. In addition, the flue gas temperature in a convective oven generally will be lower than in an oven stressing radiative heat transfer. Radiative transfer is more efficient than convective transfer above approximately 650°C For this reason, high temperature processes usually rely on radiative transfer. High temperature processes typically consume large amounts of fuel in achieving and maintaining process conditions so that conservation is a desirable process modification. The use of preheated combustion air also can raise flame temperatures to some extent, which is a desirable effect in most cases.

### 4.2.3 Fuel

The type of fuel being consumed can affect the economics of recovery significantly. Premium fuels, such as natural gas and No. 2 fuel oil, which are more costly and sometimes are in limited supply, offer a larger incentive for conservation and the implementation of heat recovery equipment than fuels such as residual oil or coal. In addition, the flue gases which result from the combustion of heavy oil and coal are harder to deal with than the gases of light oil and gas due to the ash, sulfur, metal oxides, and other contaminants in the heavier fuels.

The choice of a recuperator also depends on the fuel cost and consumption for different operating conditions. In addition, the physical state of the fuel is important in determining which combustion equipment is used. This helps determine the ability of the equipment to handle preheated combustion air. Fuel availability is not as great a constraint in equipment with dual fuel capacity and, hence, the demand for heat recovery devices for such furnaces would be smaller.

### 4.2.4 Firing and Loading Cycle

There are two methods of firing a furnace: continuously, where the furnace is not allowed to cool from the startup until it is taken out of service, and batchwise, where the furnace is heated for each operation and then allowed to cool at the end of that operation. A continuously-fired furnace will provide constant temperature flue gases to the recovery device. This will reduce the thermal cycling undergone by the recovery device, thereby reducing maintenance and increasing service life for a given piece of equipment. This would allow the use of a less expensive heat recovery device than a batch operation would.

In addition to the maintenance problems in a batch operation, some operators express doubt as to the fuel savings potential of devices that use flue gas to preheat combustion air in batch operations. They state that the major portion of fuel in a batch operation is consumed while bringing the furnace walls and plenum up to operating temperature; during this period the heat recovery device is of little value since it also is at a low temperature and, therefore, cannot serve its conservation function of preheating the combustion air. Others feel that, though there is some delay while the heat recovery device comes to operating temperature, this is minimal and installation of recovery devices still can be justified on the basis of fuel savings in batch operations. Both arguments have some validity. What is crucial is the length of the startup time for the furnace and the heat recovery device relative to the length of the batch cycle. One operator reported air preheat temperatures of 290°C immediately and a maximum temperature of 400°C after two hours. In batches operating at a maximum temperature of 400°C over a 4- to 6-hour period, the effect of the lower startup temperature is minimal.

Batch cycles suffer from several other limitations which may make the economics of waste heat recovery less favorable. Since the operating schedules of batch operations often are irregular, the waste heat usually is limited to internal uses within the furnace. Moreover, for a device designed to handle the maximum flue gas flow rate of a furnace, the recovery device on the continuous furnace has a greater potential for fuel savings than does the same device on a batch operation. Therefore, the economics of heat recovery on continuous furnaces typically will be better.

Loading cycles can be divided into batch and continuous cycles. In a continuously-loaded furnace, there would be a conveyor device to move the load through the furnace and new work would regularly be added to the furnace. At any given time, in a continuously-loaded operation, different sections of work would be at different stages of completion. In a batch operation, the work would be loaded into the furnace and completed before any new work was begun.

If a furnace is continuously-loaded, there is a premium, in most cases, to maintain the throughput in the facility. Significant costs may accrue if the furnace must be shut down for a heat recovery related problem. Additional costs also are incurred if the installation of the heat recovery equipment cannot be accomplished within normal maintenance periods or without interruption of normal operation. If the continuously-fired system requires precise, constant temperature control, a reversing regenerative heat recovery system may not be a viable option due to the variation in preheated air temperature.

In a batch system, there may be some operator resistance to the use of heat recovery devices because of a perceived difficulty in maintaining full control over furnace temperature as the load is being brought up to temperature. These concerns deal with cold loads coming in contact with high flame temperatures resulting in "hot spots" or uneven heating. These barriers are primarily attitudinal and are not valid problems to the educated and alert operator.

All batch operations, firing or loading, are subject to several common constraints. Because batch cycles usually are found on smaller and older furnaces, the managers of these operations may be less likely to invest in these areas, especially if the processes are low producers or consumers of energy, or have low load factors. Also, small batch furnaces may be involved in the manufacture of high quality specialized products. In these processes, product quality takes precedence over energy consumption. If there are any perceived risks involved in the use of waste heat recovery that could affect product quality in any way, then the justification of waste heat recovery will be much more stringent.

The combustion method affects both the flue gas temperature and composition. If the furnace is fired indirectly (flame physically separated from the load to be heated), the flue gas is more likely to be free from process-derived impurities and of a higher temperature than a direct-fired furnace. Direct-fired furnaces usually transfer heat to the load more efficiently and, therefore, the flue gas temperature and/or fuel consumption are lower. The potential for the use of waste heat recovery in indirect-fired furnaces usually is better than that for direct-fired furnaces. If major changes in a facility are being considered, it may be more energy efficient to convert indirect-fired furnaces to direct-fired ones if there are no process limitations, such as the use of special atmosphere to surround the load. The optimum policy in terms of energy conservation would be the use of direct-firing and waste heat recovery.

### 4.2.5 Firing Rate

The effect of the rate at which fuel is being consumed is obvious. The firing rate, coupled with the fuel/air ratio and the amount of air that infiltrates the flue gas stream, determine the flue gas volume that the heat recovery device will be required to handle. The flue gas rate determines the size of the heat recovery unit.

Air infiltration in the flue is an important factor affecting the choice of the heat recovery device. Unintentional leakage can be minimized but cannot be eliminated totally. Intentional air introduction can be controlled and adjusted to achieve optimum operating conditions.

### 4.2.6 Production Rate

This parameter characterizes the furnace in terms of the amount and value of the product it produces. By comparing the furnace production rate with others involved in the manufacture of the same product, or with other furnaces of the same type, the relative importance of the operation to the operator can be assessed. The larger the unit, the greater is the value of the operation and the potential for heat recovery. However, all other factors being equal, larger units hold greater waste heat recovery potential than smaller units. The production rate of a furnace is also necessary in determining the efficiency of a process in terms of energy consumed per product produced.

### 4.2.7 Pollution Control Equipment

The presence of pollution control equipment in the flue gas stream is important since it must interact and be compatible with the heat recovery equipment. If the heat recovery device is placed upstream of the pollution control equipment, the conservation equipment can serve the added function of cooling the flue gas to a temperature the pollution control equipment can handle. In the absence of heat recovery devices, the usual approach is to allow ambient air to dilute the temperature of the hot flue gases. Thus, it is more desirable to place the heat recovery device upstream of the pollution control equipment since pollution control processing will lower the temperature of the gases and make them less valuable for heat recovery. There can be limitations that could force the heat recovery equipment to be placed downstream of pollution control equipment. If there are constituents in the flue gases which are destructive (chemical attack, physical blocking, etc.) to the heat exchanger material, then the exchanger can be placed only after the harmful constituents have been removed from the flue gases. Also, space limitations due to the existing pollution control equipment may rule out upstream recuperative equipment. If upstream placement of recuperators is not possible, it is doubtful that waste heat recovery will be an economically viable option.

### 4.2.8 Heating Objective

The product and function of a furnace has a bearing on the waste heat potential of that furnace. In a melting furnace, it is important to stress radiation. The flue gas temperatures typically will be high due to the high process temperatures. The temperature driving force between the melt and combustion gases is low since the pool temperature in most industrial melts is quite high. Therefore, it is not unusual to have large amounts of energy in the flue gases of industrial melting processes. At present, it is standard practice in large glass melters and steel open hearth furnaces to have heat recovery devices.

In a drying application, high gas flow through the oven is crucial. The combustion gases act as the mass transfer medium for the substance being driven out of the load. Once the solvent has been driven out of the load and picked up by the flue gases, it must be removed from the furnace to achieve efficient drying. Though drying applications will have high flue gas flow rates at temperatures close to that of the process, there may be significant problems with the application of heat recovery devices. First, the vaporous solvent from the drying may attack the heat recovery equipment chemically. Secondly, there may be some condensation of the solvent as the flue gas passing through the exchanger cools. At this point, the liquid (or even solid) condensate may attack the exchanged surface. The heat exchanger also may be blocked physically by the deposited material. In general, any deposited material will coat the heat exchange surface and diminish its heat transfer properties. Consequently, the application of heat recovery devices in drying applications may result in low efficiencies and serious maintenance problems if proper consideration is not given to the flue gas composition.

Heating applications, such as metal treating or reheating, usually require a balance between radiative and convective heat transfer. Even though radiation is more efficient at high temperatures, convection is required to achieve uniform heating in some applications due to the "shading" problems in radiative heat transfer. Heating applications, especially those in the metals industries, show very good potential for the application of waste heat recovery technology due to the relatively high temperatures, the good flue gas flow rates, and the generally clean flue gas.

### 4.2.9 Physical Space Requirement

The heat recovery equipment options on a facility often are limited by the logistics of the furnace site; this is especially important in retrofit applications. If there is not adequate space by the furnace to site a recuperator, the costs of installation can jump sharply. Some operators have hung recuperators from the roof, buried them in the floor, or have gone to small units on the burners themselves to overcome space limitations. The maintenance costs of oddly placed recuperators also increase since the units are more difficult to service. Another logistic limitation is the difficulty in transporting a recuperator, which usually is constructed prior to installation, to the intended site. If this requires removal of a wall or roof in the furnace shop, the cost of installation also will increase greatly. The economics of many heat recovery devices are borderline, so that very high installation costs could make the difference between adoption of a technology or rejection of it.

In many older facilities space is extremely limited and the alternative uses for that space must be considered. If there is a choice between a recuperator which will save fuel or a furnace which will add to the production capabilities of the facility, in most cases the new furnace will have a higher priority than the recuperator for the remaining space in the plant.

Flue placement and burner configuration are two major factors affecting the space available for new heat recovery devices. It is not abnormal for the furnace flue to be in the roof of the combustion chamber. Since it is usually unrealistic for the heat recovery device to be set on top of the furnace due to structural limitations, the flue gas must be ducted to the recovery device. This ducting will allow the temperature of the flue gas to drop, will increase the pressure drop by disrupting the buoyant draft in the flue gas system, and generally will raise the cost of implementing waste heat recovery. If the furnace is served by a few large burners, then a centralized heat recovery device with hot air ducts to the burners would be the preferred design. If the furnace is heated by many burners, then it may be more economical to have a separate recuperative device on each burner rather than the extensive combustion air manifolding these burners would require. The most significant problems with this type of design are that there must be flue gas exit ports associated with every burner and, if the burners are tightly spaced, there may not be sufficient room to install these recuperative devices.

### 4.2.10 Heat Recovery Equipment

If a process already has some heat recovery equipment, this does not preclude the installation of additional heat recovery equipment. Even though the economic barriers will be more stringent, they are not insurmountable. In a steel soaking pit, flue gas temperatures in the 700 to 760°C range are not unusual after passing through the regenerator, but the combustion air already is preheated to 1100°C, so that other applications must be found for any heat which is recovered from the 760°C flue gas.

## 4.3 LIMITATIONS TO WASTE HEAT RECOVERY

The use of waste heat to preheat combustion air is quite straightforward in concept and theory, but significant limitations still exist in the implementation of waste heat recovery from a furnace standpoint. Barriers exist in three separate areas: technical, economic, and attitudinal.

### 4.3.1 Technical Barriers

The most pressing technical problem is the scarcity of space for heat recovery devices in retrofit applications. Industrial facilities simply are not designed with significant areas of open space to accommodate waste heat recovery devices. In many cases, the logistical problems can be overcome physically, but the cost of the solution can eliminate the profit and, hence, the motivation for the project.

The logistical problem encountered in the plant site is exacerbated by the top flue design of many industrial furnaces. This serves to complicate the problem of siting the heat recovery devices since the flue gases usually must be ducted down to the floor level device which inhibits the natural bouyant draft of the furnace. There also can be problems due to conflicts with overhead cranes and other overhead equipment in industrial plants.

The geometry of the flame from a preheated combustion air system is slightly different from that in a non-preheat system. In retrofit operations with the installation of a heat recovery device, the flame shape will change and sometimes the flame may come in contact with the walls. It then may be necessary to install a new burner.

There are certain special problems that are encountered in specific applications that must be considered. For example, little work has been done to find ways to apply waste heat recovery to furnaces which tilt, that is, move through the course of their operation. These furnaces usually are found in metal melting applications, but at present there are no efficient ways of collecting and containing the exiting combustion gases from multi-position flues. Locating the recuperator next to the furnace is not a viable solution due to the maintenance problems associated with achieving tight gas seals in the heat recovery device.

At times, the operator of a facility which has installed waste heat recovery will not use the device to save fuel. Rather, he maintains the same rate of fuel consumption, resulting in increased heat input to the furnace, and increases the product throughput in the furnace proportionally to the heat increase. This is not necessarily a bad procedure, but the furnace then is being operated above its design capacity. This generally decreases the operating life of the furnace and increases maintenance problems. Most operators are willing to sacrifice some of the capital investment in the facility to achieve the added production capacity.

The most serious problem that a furnace operator must face in the installation of waste heat recovery is being able to accurately specify the design parameters for the heat recovery device. Often operators do not have a good conception of how their furnace is operating. Even when the operator does have a good knowledge of furnace operations, heat recovery devices often are designed for average furnace operating conditions. During furnace upsets, the flue gas temperature and composition usually are not normal and can cause serious, permanent damage to the heat recovery device. This damage, primarily in the form of destroyed fins and cracked welds due to chemical attack and thermal stress, results in lower recuperator efficiency and may disrupt normal operation. To avoid this problem, heat recovery devices must be designed to withstand the worst conditions that will be encountered. As a result, these devices will be more expensive, but they also will be more likely to perform adequately over the full lifetime of the equipment.

The proper type of heat recovery device also must be specified. A regenerative recovery device is the best choice in high temperature processes with high preheat temperatures. However, regenerative systems (except for heat wheels) do not provide constant preheat temperatures, but rather cyclical temperature profiles due to the reversing nature of the regenerative system. If a process cannot withstand several hundred degree swings in the preheat air temperature, then a regenerative checkerwork cannot be used.

The regenerative heat recovery systems require that there be two sets of burners on opposite sides of the furnace, and the combustion air flow alternates from side to side. In some heating applications, the proper temperature profiles cannot be maintained in the furnace if a regenerator is used.

Conversely, a recuperative system can provide constant preheat temperatures and allow more precise temperature control within a furnace chamber. For example, in a steel reheat furnace recuperators generally are used and can achieve the three temperature zones (preheat, heat, and soak) that the process requires. The drawback of recuperators is that they cannot attain as high a preheat temperature as a regenerative system, nor can they provide long, low maintenance service like a regenerator.

Also, when operating a recuperator in a furnace that is not firing fuel continuously but is maintained hot, about one-fifth of the normal volume of combustion air will be required to keep the heat recovery device cool and to prevent a burnout of its internal devices. This factor cannot be overlooked in operation and should not be overlooked when assessing the efficiency of the recuperator.

Severe maintenance problems are quite frequent in present recuperator installations due to improper specification of process conditions. This has helped to establish certain negative prejudices in those who decide whether to install heat recovery or not. The economics of heat recovery usually are marginal to begin with, so that negative performance information on heat recovery devices can make their use quite unattractive.

### 4.3.2 Economic Barriers

In general, unfavorable economics limit the application of most heat recovery devices; that is, the technical problems have solutions, but they are expensive. Even at low flue gas temperatures heat can be recovered and combustion air preheated, but the relatively small amount of fuel savings that results does not warrant the capital investment in the heat recovery device.

At present, there are two principles on which operators justify expenditures on heat recovery devices: fuel availability and fuel cost. In the absence of any unusual barriers, an operator will invest in heat recovery if the fuel savings from the equipment can achieve the return on investment that the operator requires for use of his capital. In some cases, however, heat recovery need not meet such rigid requirements. If the operator foresees significant problems with fuel availability, then the investment in energy conservation equipment can be justified by the fact that it will allow the furnace to maintain production at or near regular levels, even if the operator's fuel supplies are reduced. The use of fuel availability as a justification for investment in heat recovery equipment varies depending on the plant, the process, and the attitude of the operator. However, these factors are dependent on the process fuel supply situation and how crucial the furnace product is to the producer's profit.

### 4.3.3 Attitudinal Barriers

Beyond potential economic barriers, the most serious problem affecting waste heat recovery is a psychological aversion to the technology by many operators. In a very real sense, many industrial operations are still an art rather than a science. For this reason, many operators are reluctant to make any changes in operating procedures that may result in reduced furnace life or increased furnace maintenance. While many installations publicize the grand successes and extraordinary rates of return they have achieved, many more operators speak of the severe operating difficulties they have experienced with heat recovery devices. The opinions of fellow operators weigh very strongly with the decision makers. The maintenance problems of the past can be avoided through knowledgeable design and careful operation, but this must be exhibited consistently before waste heat recovery technology can be accepted fully by those who operate industrial facilities.

Related to the reluctant acceptance of waste heat recovery is the operators' attitude that energy conservation is not a goal in itself, but simply one of many ways of lowering operating costs. Indeed, some operators only think of energy conservation when product demand is low and costs must be trimmed. In times of high demand, production is the sole important factor and energy efficiency is relatively immaterial.

## 4.4 CONCLUSION

The selection of heat recovery equipment depends upon many factors. If most of these factors are taken into account when ordering new heat recovery devices, one can be fairly certain of getting the right equipment for the process. Table 31 lists typical furnace types and some factors affecting heat recovery. (Numbers in parenthesis on the table indicate the references for each factor.)

In some applications, while difficulties such as space limitations exist, there are no technical limitations in overcoming these difficulties. However, the economics may preclude the installation of heat recovery devices in certain plants because the fuel savings do not justify the installation and/or maintenance costs.

The operators also need to look at fuel savings and conservation as an end in itself rather than just another way of reducing operating costs. Such an attitude change would be a significant step towards the widespread use of heat recovery equipment.

# TABLE 31. MAJOR FACTORS AFFECTING HEAT RECOVERY

| Furnace type | Operation | Materials | Production rate | Number of Btu's consumed/ unit product | Firing method | Loading cycle | Firing cycle | Fuel type | Process temperature (°F) | Flue gas temperature (°F) | Heat transfer | Heat recovery | Pollution control equipment (% industry with control) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Open Hearth | Refining | Steel | 10-100 Tons/hr | 4.3-6x10 Btu/ton<br>(5) | Direct | Batch<br>(6) | Continuous-reversing<br>(11) | Coke oven gas<br>Natural gas<br>Oil<br>(3) | 2800-3100° | 1500° | Radiation | Yes<br>(3) | Yes<br>(16%) |
| Basic O | Refining | Steel | 100-300 Tons/hr | 7x10 Btu/ton | N/A | Batch<br>(6) | | Oil<br>Natural gas<br>(3) | 2800-3000° | 1200-1500° | Conduction<br>Convection | | Yes<br>(76%) |
| Soaking Pit | Reheating | Steel | 30-100 Tons/hr/ 1000 sq ft<br>(3) | 1.5x10 Btu/ton<br>(3,5) | Direct<br>(5) | Batch<br>(6) | Intermittent<br>(11) | By-product fuels (i.e., coke gas, pitch)<br>(3,5) | 1400-2500°<br>(5,8,11) | 1000° with heat recovery; 2200° w/out heat recovery<br>(5) | Radiation | Yes<br>(3) | No |
| Pusher Type | Reheating | Steel | >300 Tons/hr<br>(3) | 3-5x10 Btu/ton<br>(3) | Direct<br>(11) | Continuous<br>(1,6) | Continuous<br>(11) | Oil<br>Natural gas<br>Coke oven gas<br>(3) | 2100-2500°<br>(1,11) | 1200-1500° | Convection<br>Radiation | Yes | Yes<br>(small %) |
| Rotary Hearth | Reheating | Steel | >60 Tons/hr<br>(3,17) | 3-5x10 Btu/ton<br>(3) | Direct<br>(11) | Continuous<br>(6) | Continuous<br>(11) | Oil<br>Natural gas<br>(3) | 2100-2300°<br>(8) | 1700°<br>(5) | Convection<br>Radiation<br>(12) | No<br>(12) | Yes<br>(90%) |
| Walking Scan | Reheating | Steel | 50 Tons/hr<br>(8) | 2-5x10 Btu/ton<br>(3) | Direct<br>(11) | Continuous<br>(1,6) | Continuous<br>(11) | Oil<br>Natural gas<br>(3) | 1400-2000°<br>(8) | 2100° | Convection | Yes<br>(14) | |
| Box Annealing | Annealing | Steel | 1.0-10.0 Tons/hr<br>(8) | 2.5x10 Btu/ton<br>(5) | Indirect or Direct<br>(11) | Batch<br>(3,6) | Continuous<br>(11) | Oil<br>Natural gas<br>(3) | 1500-1700°<br>(8,11) | 1000°<br>(5) | Convection<br>(13) | No<br>(13) | |
| Bell Annealing | Annealing | Steel sheets and strips | 35-400 Tons/charge<br>(17) | 2x10 Btu/ton<br>(3) | Indirect or Direct<br>(3) | Batch<br>(3) | | Oil<br>Natural gas<br>(3) | 1500-1700°<br>(11) | 1500° | Radiation<br>Convection | | |
| Slot Forge | Heat treating | Steel sheets | | 4-9x10 Btu/ton<br>(12) | Direct<br>(6) | Batch/ Continuous<br>(3) | Continuous<br>(12) | Oil<br>Natural gas<br>(3) | 2400°<br>(4) | 2400°<br>(4) | Convection<br>Radiation<br>(12) | Yes | |
| Roller Hearth | Heat treating | Sheet metal | >300 Tons/hr<br>(3) | 1.9x10 Btu/ton | Direct<br>(11) | Continuous<br>(1) | Continuous<br>(11) | Oil<br>Natural gas<br>(3) | 2200-2600°<br>(3,11) | | Radiation<br>Convection | | |
| Car Bottom | Annealing | Steel<br>Aluminum | >480 Tons/hr | 2-3x10 Btu/ton<br>(5) | Indirect or Direct<br>(3) | Batch<br>(3,6) | Continuous<br>(1) | Oil<br>Natural gas<br>(3) | 750-1400°<br>(1,5) | 1400°<br>(5) | Radiation<br>Convection | | |
| Reverberatory | Melting | Aluminum | 5-100 Tons/hr<br>(15) | 6-7x10 Btu/ton<br>(5) | Direct<br>(11) | Batch/ Continuous<br>(6) | Intermittent<br>(11) | Natural gas<br>Oil<br>(5) | 2200-2800°<br>(5) | 1600°<br>(5) | Radiation<br>Convection<br>(3) | Yes<br>(10) | Yes<br>(45%) |
| Radiant Hood Ignition | Sintering | Iron Ore | 1500-10,000 Tons/day<br>(3) | 1.7x10 Btu/ton<br>(3) | Direct<br>(6) | Continuous<br>(6) | Continuous<br>(3) | Coke and breeze<br>Natural gas<br>(3) | 2400-2700°<br>(3) | 250-310° | Radiation | | |
| Vertical Shaft | Pellitizing | Iron Ore | 1200 Tons/day<br>(3) | .6x10 Btu/ton<br>(3,5) | Direct<br>(6) | Continuous<br>(6) | Continuous<br>(2) | Natural gas<br>Oil<br>(3) | 2300-2500°<br>(3) | 500-900°<br>(10) | Radiation | Yes<br>(7) | Yes<br>(% unknown)<br>(2) |

# TABLE 31. (continued)

| Furnace type | Operation | Materials | Production rate | Number of Btu's consumed/ unit product | Firing method | Loading cycle | Firing cycle | Fuel type | Process temperature (°F) | Flue gas temperature (°F) | Heat transfer | Heat recovery | Pollution control equipment (% industry with control) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Traveling Grate | Pellitizing | Iron Ore | 100-300 Tons/hr<br>(3) | .6-.7x10 Btu/ton<br>(3,5) | Direct<br>(6) | Continuous<br>(6) | Continuous | Coal<br>Natural gas<br>Oil<br>(3) | 2300-2500°<br>(3) | 300-500°<br>(2) | Radiation | Yes<br>(2) | No |
| Grate Kiln | Pellitizing | Iron Ore | 200-300 Tons/hr | .6x10 Btu/ton<br>(5) | Direct<br>(6) | Continuous<br>(6) | Continuous<br>(11) | Natural gas<br>Oil<br>(3) | 2300-2500°<br>(3) | 300-600°<br>(2) | Radiation | Yes<br>(2) | Yes<br>(% unknown)<br>(2) |
| Cupola | Melting | Iron | 1-35 Tons/hr | 1.5x10 Btu/ton<br>(5) | Direct<br>(6) | Batch<br>(6) | | Natural gas<br>Oil<br>(1) | 1800-2900°<br>(3) | 1000-1500°<br>(5) | Conduction<br>Convection | Yes<br>(3) | Yes<br>(60%) |
| Blast Furnace | Heating | Iron | 1000-10,000 Tons/day | 1.5-2.5x10 Btu/ton<br>(3,5) | Direct<br>(6) | Continuous<br>(6) | Continuous | By-product fuel (i.e., coke, gas)<br>(3) | 2500-2800°<br>(5) | 1000-1500° | Conduction<br>Convection | Yes<br>(3) | Yes<br>(% unknown)<br>(3) |
| Continuous (Regenerative) Tank | Melting | Glass | 10-1000 Tons/day | 4-10x10 Btu/ton<br>(3) | Direct<br>(11) | Continuous | Continuous<br>(11) | Natural gas<br>Oil<br>(5) | 2400-3000°<br>(5,11) | 800-1500°<br>(5) | Radiation | Yes<br>(5) | No |
| Day Tank | Melting | Glass | 2-10 Tons/day<br>(1) | 12x10 Btu/ton<br>(1) | Direct<br>(1) | Batch<br>(6) | Intermittent | Natural gas<br>Oil<br>(3) | 2600-2800° | 1500°<br>(5) | Radiation | Yes<br>(1) | No |
| Rotary Kiln | Calcining | Limestone | 50-100 Tons/day | 8.5x10 Btu/ton<br>(16) | Direct<br>(11) | Continuous<br>(6) | Continuous<br>(11) | Coal<br>Natural gas<br>(3) | 2000-2500°<br>(1,11) | 750-1300° | Radiation | Yes<br>(1) | |
| Rotary Kiln | Calcining | Cement | 35 Tons/hr<br>(3) | 8.5x10 Btu/ton<br>(16) | Direct<br>(11) | Continuous<br>(6) | Continuous<br>(11) | Oil<br>Natural gas<br>Coal<br>(5) | 2800-3000°<br>(11) | Dry process-1000°<br>Dry w/pre-heater-600°<br>Wet process-600°<br>(5) | Radiation | Yes<br>(1) | |
| Fluidized Bed Calcining | Calcining | Gypsum | 221-400 Lbs/hr | | Indirect<br>(6) | Batch/ Continuous<br>(6) | | Gas<br>Oil | 400-2000° | | Radiation<br>Convection | Yes | Yes<br>(% unknown) |
| By-product Coke Ovens | Pyrolysis | Coke and coke oven gas | 18-25 Tons/charge | 2.8-3.5x10 Btu/ton | Indirect<br>(6) | Batch<br>(6) | Continuous | By-product fuels (i.e., coke oven gas)<br>(3) | 1800-2450°<br>(11) | 1200° | Conduction<br>Radiation | Yes | Yes<br>(99%) |
| Tubestill Heaters | Heating | Petroleum | 10-70 Bbl/day | .08x10 Btu/bbl | Indirect<br>(6) | Continuous<br>(6) | Continuous | Natural gas<br>(3) | 650-1500°<br>(3) | | Radiation | Yes | No |
| Rotary Dryers | Heating and drying | Slimes, Minerals, Organic Products | 50-60 Tons/day | | Direct<br>(6) | Continuous<br>(6) | Continuous | | 1000-1400° | 300° | Radiation<br>Convection | No | Yes<br>(<10%) |
| Pit | Normalizing Hardening Annealing | Heavy Press Forgings | 60-400 Lbs/hr | .9x10 Btu/ton | Direct<br>(11) | Batch<br>(6) | Intermittent<br>(11) | Natural gas | 2150-2250° | | Radiation<br>Convection | | |
| Tunnel Kilns | Heating and firing | Ceramics | | 10-30x10 Btu/dozen | Direct<br>(6) | Continuous<br>(6) | Continuous<br>(1) | Fuel gas<br>Oil<br>Coal | 1800-3200°<br>(11) | | Convection<br>Radiation<br>(11) | Yes<br>(11) | |
| Boiler Hearth | Firing | Flooring Tiles, Electronics | <300 Tons/day | | Direct<br>(11) | Continuous<br>(6) | Continuous<br>(11) | Natural gas | 800-2300° | | | | |
| Shuttle Kiln | Heating and firing | Sanitary-ware Electronics | | 19x10 Btu/ton | Direct | Batch<br>Intermittent<br>(6,11) | | Natural gas<br>Fuel oil<br>(3) | 2500°<br>(5) | 500°<br>(5) | Convection<br>Radiation | Yes<br>(11) | |
| Conveyor Furnace | Drawing Annealing Normalizing | Nuts Bolts Auto Parts | 105 Tons/hr | | Indirect/ Direct<br>(3) | Continuous<br>(6) | Continuous<br>(8) | Natural gas | 1300-1500° | | Convection | | |
| Paint Drying Oven | Curing | Decorated cans | | | Indirect<br>(6) | Continuous<br>(6) | Continuous | Hydrocarbon Solvent Vapor<br>Natural gas | 1000° | 250° | Conduction | | Yes<br>(% unknown) |

Note: T (°C) = (T (°F)-32)/1.8 M (kg) = M (lb)/2.21 E (J) = E (Btu) x 1055

## REFERENCES FOR TABLE 31

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# 5. AVAILABILITY OF BURNERS USING HIGH TEMPERATURE AIR

## 5.1 INTRODUCTION

Waste heat recovery is one of a number of energy conservation technologies currently being studied by industry. A major waste heat recovery technology involves preheating combustion air. Until now, the effect of an increase in combustion air temperature on industrial burners has been unclear.

Currently, burners are available which, within certain limits, can use high temperature combustion air, with a few models designed for temperatures as high as approximately 750°C. However, standard burners also can be modified slightly to handle limited, but significant, amounts of preheated air. Therefore, industry more than likely will use modified standard burners in waste heat recovery systems.

The major limitations on the development of high temperature burners stem from lack of demand and difficulty in obtaining appropriate construction materials. The demand for high temperature preheat combustion equipment is related closely to the demand for waste heat recovery devices. As fuel prices increase and fuel becomes scarce, the economics of energy conservation will favor use of waste heat recovery. Burner modification could account for a noticeable increase in fuel savings without affecting the market for high temperature burners. However, as fuel prices continue to increase, the incentive probably will exist for carrying out the necessary research to further the development and manufacture of high temperature burners.

This chapter discusses the availability and development of these high temperature burners and the benefits and limitations of waste heat recovery. It also describes the effects high preheat temperatures have on ancillary equipment as well as burner cost comparisons.

## 5.2 BENEFITS OF HIGH TEMPERATURE PREHEAT

The economic advantages of waste heat recovery include decreased fuel consumption and a potential increase in productivity. Decreased fuel consumption not only reduces fuel bills but also brings about a decreased reliance on fuel supplies. Although fuel conservation is an important factor to many manufacturers, it is not the predominant consideration. The most important benefit of reduced fuel consumption is reduced operating costs. Decreased fuel consumption is just one of many ways to reduce operating costs. As a result, as long as fuel is available at a reasonable price, manufacturers will not give conservation their highest priority.

Even though productivity is increased because of installing waste heat recovery equipment, most operators would not consider the increase in productivity alone to be a reason to install equipment. Productivity increases are considered just an added benefit with insignificant economic value when compared to fuel savings and independence.

## 5.3 HIGH TEMPERATURE PREHEAT IMPLEMENTATION SCENARIOS

There are three different temperature ranges for preheated combustion air with low temperature being the most efficient. The benefit gained by an increase in air preheat temperature from ambient to 260°C is greater than the incremental benefit gained between 260 and 540°C. Likewise, the 260 to 540°C temperature increase benefit is greater than that gained between 540 and 820°C. This effect becomes more pronounced the higher the exit gas temperature becomes and whenever the percent excess air is raised. Thus, the least expensive modifications return the largest efficiency increment with the gradual increase in fuel savings from installing sophisticated preheat equipment diminishing as each successively higher temperature is attained.

The largest benefits per dollar invested would be achieved if a recuperator is installed to increase air preheat temperatures without significantly altering the combustion system. For this to occur, the ambient temperature combustion air system currently on line must be made to accept preheated combustion air with a low temperature.

At approximately 400°C air preheat temperature, it becomes necessary to replace the original burner and portions of the ancillary system. In many cases, the high temperature equipment is fabricated from readily available stainless steel. Such major modifications in the construction system make the waste heat recovery cost significant.

In the medium temperature range, there is a substantial increase in equipment investment, along with a decline in efficiency. Therefore, if a company can elicit the benefits of low air preheat with their ambient air system, there is little incentive to move the medium preheat range.

For those companies that do not have the option of using low temperature preheated air, a move into the medium preheat range may be better than choosing the highest preheat temperature range, since there is an even greater increase in equipment cost at the higher temperatures as well as a decline in efficiency. Although the burners used at the highest feasible temperatures are expensive, their cost is small compared to the cost of both the total combustion system and the waste heat recovery device. The main factor contributing to the increased cost of high temperature equipment is the expense of necessary heat resistant materials.

Improvements in waste heat recovery technology, caused by an increasing apprehension over security and price of fuel supplies, will lead to a decrease in the air preheat temperature that maximizes combustion system efficiency.

## 5.4 LIMITATIONS ON HIGH TEMPERATURE COMBUSTION AIR PREHEAT

There are only a few, if any, theoretical obstacles to using high temperature combustion air. Aside from the lack of economic incentive, there are considerable construction materials problems which have not been solved. A spokesman for a burner manufacturing firm examining the use of high temperature combustion air said air preheat temperatures of 1650°C theoretically would not cause problems for properly constructed nozzle mix burners. However, materials problems occur when an actual attempt is made to construct such a burner. Specifically, there is the problem of developing an alloy that can withstand the assault of high temperature operation. At present, no domestic company manufactures a burner which can handle air preheated to temperatures over 1000°C.

The use of preheated air in premix burners is considerably more uncertain. Premature combustion and the possibility of flashback make the use of high or medium temperature preheat air out of the question and severely limit the use of low temperature preheat air. Although burner manufacturers disagree on the exact auto ignition temperature, it is reasonable to assume, for natural gas, premature combustion occurs at air preheat temperatures well below 540°C. The auto ignition temperature is a function of the type of fuel and burner used.

There are three critical temperatures that divide the preheated air temperature spectrum:

- The upper limit or failure point for ambient air systems is 400°C.
- The upper limit or failure point for most modified steel systems is 540°C.
- The upper limit or failure point for the majority of custom-made high temperature systems is 760°C.

Few companies offer combustion equipment for air temperatures greater than 760°C and even these available systems are expensive and complex. A number of companies feature shelf burners capable of using preheated air in the range of 600 to 650°C, while a smaller number of companies feature custom burners which surpass that limit. Even then, industry is unwilling to buy large amounts of preheat equipment, thereby suggesting that either the combustion system's efficiency is maximized at a lower preheat temperature or that industry is unaware of the waste heat recovery system's capabilities.

The currently manufactured high temperature burners have difficulty generating all the flame types used in industry. For example, a short, flat flame cannot be used with preheat combustion air because the high temperature zone of the flame is too near the nozzle. While ordinary burners may be able to change from one flame type to another without harming the burner, high preheat temperatures and resulting high flame temperatures usually are not feasible with current burner design. The system changes and the reasons behind them are outlined in the sections below.

### 5.4.1 260°C to 400°C

Most standard industrial burners are fabricated from either cast iron or carbon steel. At temperatures in the 260 to 400°C range, both materials show signs of growth and distortion. These dimensional changes in materials alter orifice sizes, cause joints to break, and usually lead to burner failure.

However, most cold air burners can operate with preheated air as long as the metal temperature remains below the metal failure point. To keep the temperature below the failure point, it is necessary to pay careful attention to the quantity of air and fuel entering the burner. As the temperature of the combustion air increases, the amount of fuel necessary to maintain a given furnace production rate decreases. When the amount of fuel decreases, the amount of air necessary to combust the fuel decreases also.

All these factors must be taken into consideration when adjusting the fuel/air intake at higher temperatures. The first step in restructuring the air and fuel intake after changing to preheated air is to diminish the fuel entering the burner according to its increased efficiency. The required mass of combustion air then is calculated. Taking into consideration the decreasing density of air at higher temperatures, a new volume flow rate for preheated air is calculated. The pressure drop across the burner is proportional to the square of the ratio of hot to cold air flow rates.

In summary, air mass requirements can be lowered by air density diminishing at a faster rate than increasing fuel efficiency. At higher air temperatures, the flow rate of air must increase. This increase causes a much larger pressure drop across the burner. The end result may be burner instability due to high air velocity and inability of the combustion air supply source to meet the new burner pressure requirements. It also may be necessary to increase blower size in forced draft furnaces or increase blower capacity in natural draft furnaces in order to increase the air flow rate.

### 5.4.2 400°C to 540°C

When using air preheat temperatures in the 400 to 540°C range, most manufacturers suggest using stainless steel burner models with some modifications. Stainless steel is usually nickel chromium alloys which have high resistance to oxidation and corrosion. This resistance to oxidation is important because the oxygen in combustion air attacks steel when the temperature rises. The addition of cobalt to steel alloys also can reduce oxidation.

The stainless steels used in burners are usually 300 series alloys and are reliable at temperatures well above 540°C. It is necessary to fabricate only those components which will come in contact with either the high temperature air or the flame itself from these alloys, not the entire burner. For instance, the main burner body and burner head are both part of the combustion air path and are likely to be of stainless steel.

When operating at high air preheat temperatures, it is important to insulate the fuel supply from the heat of the air supply. If the fuel supply rises above 370°C cracking of hydrocarbons becomes a potential problem. The result of cracking is carbon deposits in the fuel line and in the fuel orifices. Both of these hinder burner operation by altering the fuel flow pattern. This ultimately affects the air/fuel mixture and, hence, the flame pattern. For example, an increase in oil temperature will form carbon deposits that clog the fuel line and change the atomizer fuel spray characteristics. This, in turn, alters the quantity, pressure, and direction of the spray leaving the atomizer. The increase in temperature also will increase vaporization and enhance mixing to the point where oil flame length can change noticeably with small air preheat temperature changes.

The effect the adjacent high temperature air line has on the fuel supply system depends to a large extent on the fuel velocity. The longer the fuel remains in contact with the hot air, the greater the possibility of cracking. The influence of the hot air is tempered by the nature of the materials that separate it from the fuel. In many instances, a refractory is used to insulate the fuel line and the outside casing from the hot combustion air. Due to the geometric integrity of the refractory shapes, crack formation can occur without lining failure.

Many high temperature burners are large because of the refractory material thickness. Larger air manifolds are also necessary due to the decreased air density. The refractory either may be cast, rammed, or consist of ceramic fibers which have the benefit of being lighter and less bulky than the other refractory materials and thus cut down the overall size. Another way to decrease overall size is to increase the combustion air line pressure. To accomplish this, it may be necessary to increase blower size on the combustion air line. If the air pressure is raised, it then is possible to increase the air flow rate through smaller tubes. If flame stability can be maintained, it is possible to have compact high temperature burners.

### 5.4.3 Over 540°C

When manufacturing burners for use with preheated air at temperatures significantly greater than 540°C it is necessary to change metals. Alloys with high levels of nickel and chrome (such as Inconel) were chosen as the best materials for high temperature applications. The major problem with the high quality alloys is supply scarcity. One burner manufacturer advised that there is a one year wait for these alloys. A number of burner manufacturers agreed that preheat air burners can be constructed for virtually any temperature range if the wide range of heat resistant materials are available.

Most of the high temperature burners that incorporate refractory linings use a relatively low temperature ceramic material which remains satisfactory up to about 760°C If the air preheat temperature exceeds that level, it is necessary to change the burner lining. Problems also arise with failure of the burner block at extremely high temperature air preheat. One burner manufacturer claimed that adding alumina to the casting compound is a common solution to the problem of raising the rating of the burner refractories.

## 5.5 EFFECTS ON ANCILLARY EQUIPMENT

Ancillary equipment in a combustion system provides measured quantities of fuel and air to the burner. Ancillary equipment consists of an air source, a blower, the manifolds connecting the fuel and air sources to the burner, and the meters and gauges which measure, control, and record the flow.

Two possible ways to increase the air flow rate into the burner are: (1) to increase the blower size along with the size of the burner and supply apparatus in a natural draft furnace, and (2) in the case of a forced draft furnace, either the size of the air supply apparatus must be increased or the blower must exert more force on the air stream to overcome the increased pressure drop across the burner. In nonretrofit applications the air density is taken into account when designing the system. Thus, the burner air supply apparatus and the air line supply machine are both likely to be larger.

When the preheated air is transported to the burner, the air temperature must be maintained. To accomplish this it is necessary to employ insulation to avoid heat loss to the surrounding area and to use piping or ductwork that will not fail under heat stress. In some cases it may be necessary to include expansion joints between air duct sections to account for temperature induced metal expansion. The grade of steel employed in the ductwork depends on the temperature of the preheated air.

Once the air is at the burner installation it is necessary to control the flow reaching the furnace. This can be done by either hot metering or cold metering, which refer to the relationship of the meter to the waste heat recovery device. In cold metering the air stream is controlled prior to entering the recuperative device. This system is the simplest air flow control method since the air always is measured at ambient temperature and the density is constant. The velocity of the air flow past orifices and other obstructions depends on the quantity of air and the temperature.

The cold metering system has a number of drawbacks. If the hot gas stream flowing out of the recuperator has numerous target burners, there is no way to differentiate between the supply reaching the various burners; thus the system is limited to one zone of burners per recuperator. Another problem is that the recuperator may leak and the readings taken on the cold air side would not reflect this defect, throwing the fuel/air ratio out of balance.

The chief advantage of the cold air system is that it usually has less components since only one flow is measured. These components are cheaper than hot air components since they do not compensate for fluctuating densities and they do not need to be heat resistant.

If it is possible to regulate or accurately predict the preheat air temperature, then it may be possible to use cold air components for hot air metering. Where there is a steady temperature, a steady density also exists. Once adjusted, the system would register properly if the temperature remains constant. Provided the cold air components are heat resistant, hot air metering would reflect waste heat recovery device leakage at no additional cost. It then would be possible to use this method of metering in a multi-zone furnace by using duplicate sets of gauges provided the temperature remained constant for all zones.

In systems where the air temperature fluctuates, it is necessary to measure the mass flow air/fuel relationships with a temperature compensation apparatus. As stated previously, when the air temperature increases, the necessary amount of fuel decreases, and hence, the air mass required for combustion decreases proportionately. Concurrently, however, the density of air decreases much faster than the need for air and the net result is an increase in air flow rate. Therefore, it is necessary to constantly vary the air and fuel rates with the air temperature. Constant temperature compensation becomes a requirement of efficient operation. Again, depending on the number of zones, one or more systems will be necessary. These systems are relatively expensive due to the nature of the equipment required such as digital electronic devices for computing flow rates based on air temperature.

## 5.6 COST COMPARISONS

Combustion system costs increase with the number of fuels being combusted and the temperature at which they are being burned. For example, the price of a dual gas/light oil burner ranges from 1.2 to 2 times the cost of an equivalent gas burner. If the burner also is being designed for heavy oil, then the price will increase to 1.5 to 3 times the cost of the gas burner. In both cases, the deviation from a linear change in price with additional fuels is a result of both fuels sharing the same combustion air equipment.

Stainless steel burners are required with medium preheat temperatures. These burners cost up to three times as much as their comparable carbon steel or cast iron counterparts. If higher quality alloys are required, the cost can rise an additional 50 percent. Hot air combustion systems, not including recuperators, usually cost twice as much as comparable cold air systems. This multiple rises with the required sophistication of the hot air system.

The main drawback in using high temperature burners in new installations is not the increased cost of the burner itself, but rather, the cost of the associated combustion air system and waste heat recovery device. The burner cost comprises only about 10 to 20 percent of the combustion system costs. In many instances the total combustion system only comprises a fraction of the waste heat recovery system. Combustion systems include ductwork, controls and burner, and air source, windbox, or blower. The waste heat recovery system includes additional ductwork as well as the recuperator.

Included in the major factors discouraging retrofit applications are capital expenditures, as well as difficulty in installing the larger high temperature equipment. According to one construction company, in retrofit operations ductwork alone may cost six times as much as the combustion system. Retrofitting combustion equipment is significantly more expensive than using the same equipment in a new installation because many industrial furnaces are placed close together and cannot accommodate the larger high temperature equipment. Even if the physical space were available, it is likely to be crowded and operating and maintenance costs will increase. These problems are compounded further by the diminishing fuel savings which accrue at higher temperatures. Nonetheless, one or two high technology firms successfully have marketed extremely high temperature air preheat burners using air temperatures up to 1000°C.* The advantage of these burners, as well as all hot air burners, is that they meet the same furnace production requirement with a burner compliment using less fuel and having a lower kJ/hr rating.

## 5.7 CONCLUSION

While more efficient fuel utilization results in lower operating costs, many operators do not consider this their highest priority since they believe that the percentage reduction in operating costs is not large enough to justify the investment in heat recovery devices. As long as fuel is priced reasonably and supplies are reliable, conservation will not be the predominant concern of the operators.

Ordinary burners require modification if they are to use air that is preheated to greater than 400°C The greater the preheat, the more modification is needed both in design as well as in construction materials. However, modifications of the combustion system cost only a fraction of the total retrofit cost of the waste heat recovery system.

Thus, it is generally more difficult, as well as more expensive, to operate high temperature equipment than it is to operate ambient air systems. The addition of a temperature component to the combustion equation adds another complex dimension to controlling the fuel/air ratio.

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* 1000°C was given as the air preheat temperature achieved by a self-recuperative burner manufactured by Hotwork, Inc., Lexington, Kentucky.

# 6. THE IMPACT OF WASTE HEAT RECOVERY ON THE FORMATION AND RELEASE OF AMBIENT POLLUTANTS

## 6.1 INTRODUCTION

The previous sections have discussed the potential for waste heat recovery and the methods by which energy conservation can be accomplished in industrial combustion facilities. Facilities which implement waste heat recovery can impact emission levels of those pollutants specifically associated with the burning of fossil fuels, namely total suspended particulates (TSP) and sulfur dioxide ($SO_2$). By using waste heat recovery devices, required fuel consumption is reduced, thereby reducing TSP and $SO_2$ emissions. This reduction is directly proportional to the absolute reduction of fuel consumption.

To compute the decrease in emissions, it is necessary to first calculate the decrease in fuel consumption. This is done using a series of primary and secondary mass and energy balances around a model furnace and recuperator system (see Figure 43 ). Fuel consumption is calculated by using the relations and the air/fuel ratio and solving for fuel flow rate.

Figures 44 and 45 dipict the decrease in fuel consumption with increasing air preheat in a 540°C furnace at 0 percent and 15 percent excess air, respectively. The fuels considered are natural gas, medium Btu gas 1 (e.g., Koppers-Totzek) and medium Btu gas 2 (e.g., Lurgi), low Btu gas 1 (e.g. Wellman-Galusha), low Btu gas 2 (e.g., Winkler), and hot raw low Btu gas (540°C). The results show a decrease in fuel consumption of up to 19 percent. A similar decrease in $SO_2$ and TSP can be anticipated.

Waste heat recovery also impacts $NO_x$ emission levels. Nitrogen oxide, specifically thermal $NO_x$, increases with the addition of recovery devices. A separate model was developed to establish the $NO_x$ emissions effects. The basic assumption of the emission reduction models for TSP and $SO_2$ was that conservation techniques would reduce emissions, which is not true with $NO_x$; therefore, another system was developed. By comparing the $NO_x$ increase resulting from the addition of conservation devices versus the savings gained by reducing fuel consumption and subsequently energy costs, the net impact of waste heat recovery on $NO_x$ emissions can be determined.

Nitrogen oxides ($NO_x$) emitted in flue gases from industrial combustion originate from two processes: (1) the fixation of nitrogen in combustion air, which is thermal $NO_x$, and (2) the oxidation of chemically bonded nitrogen in solid and liquid fuels, which is fuel $NO_x$. For most gaseous fuels, the nitrogen content is very low compared to liquid and solid fossil fuels, thus thermal $NO_x$ makes up a large part of all $NO_x$ emissions for gaseous fuels.

Fuel $NO_x$ reactions are as fast as the combustion reactions taking place in the flame and estimation of fuel $NO_x$ emissions has to take the combustion kinetics into account. Fuel $NO_x$ formation and destruction is estimated by considering mechanisms of several reactions, most of which can be represented

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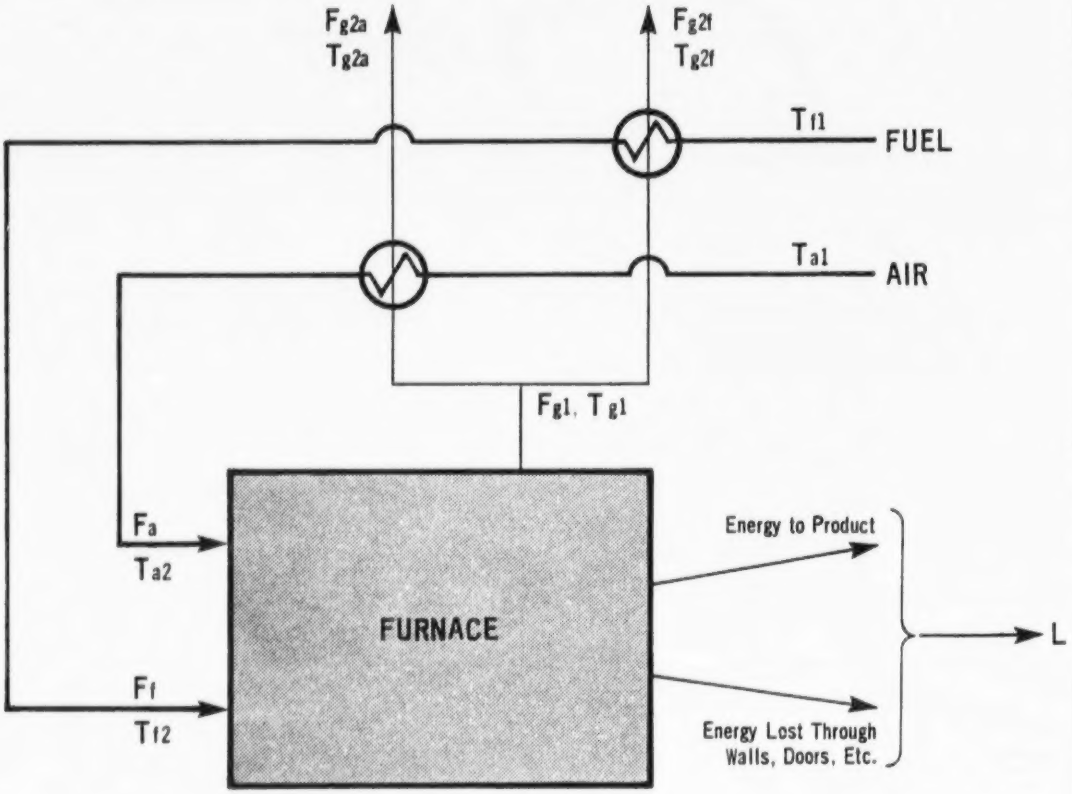
$F_{g2a}$
$T_{g2a}$
$F_{g2f}$
$T_{g2f}$
$T_{f1}$
FUEL
$T_{a1}$
AIR
$F_{g1}$, $T_{g1}$
$F_a$
$T_{a2}$
$F_f$
$T_{f2}$
FURNACE
Energy to Product
Energy Lost Through Walls, Doors, Etc.
L

L = Load
T = Temperature (° K)
F = Flow (Moles/time)
f = fuel
a = air
g = flue gas
1 = before recuperator
2 = after recuperator

Figure 43. Model furnace energy inputs and outputs.

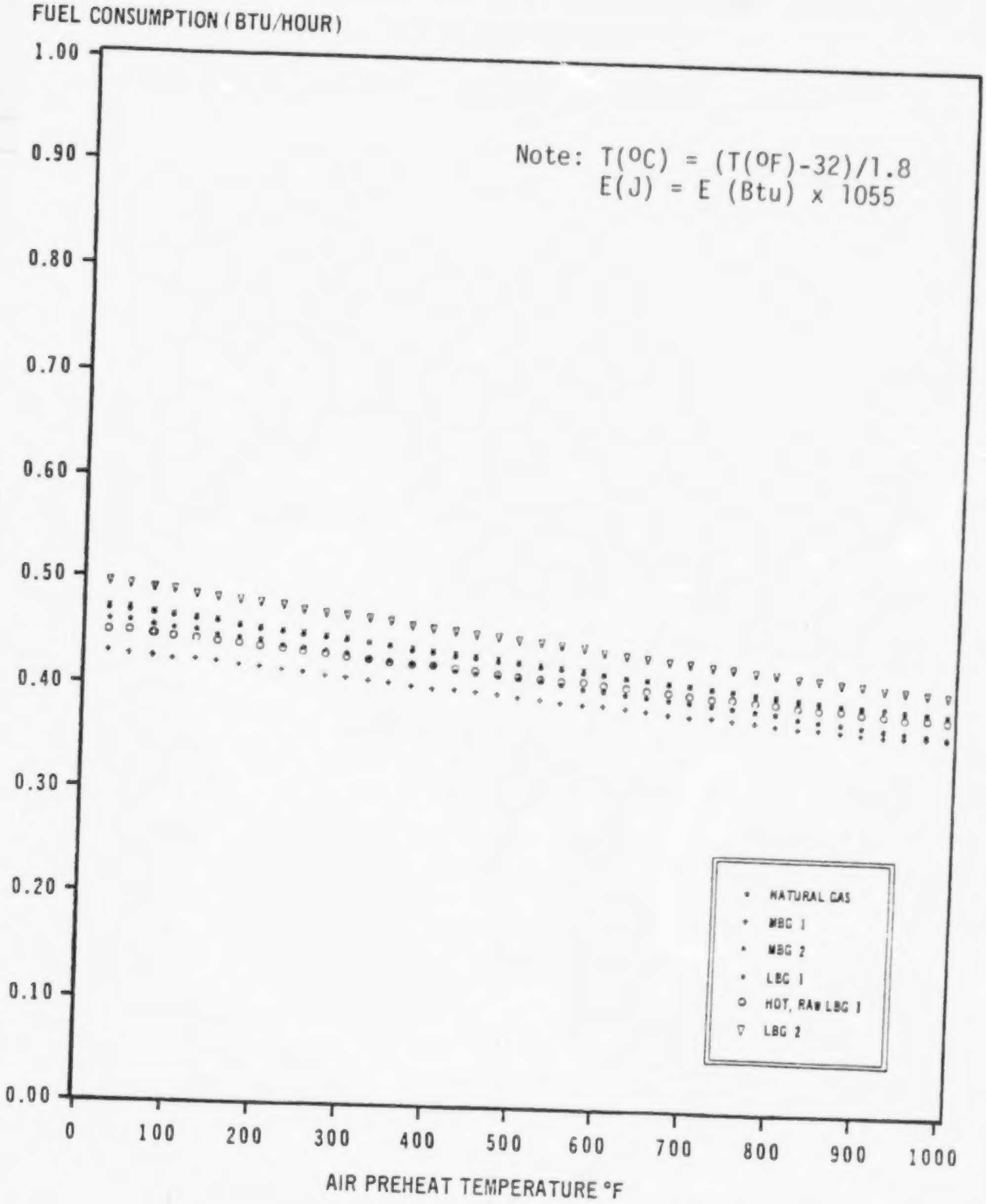

Figure 44. Furnace fuel consumption versus air preheat temperature for 540°C (1000°F) furnace with 0% excess air.

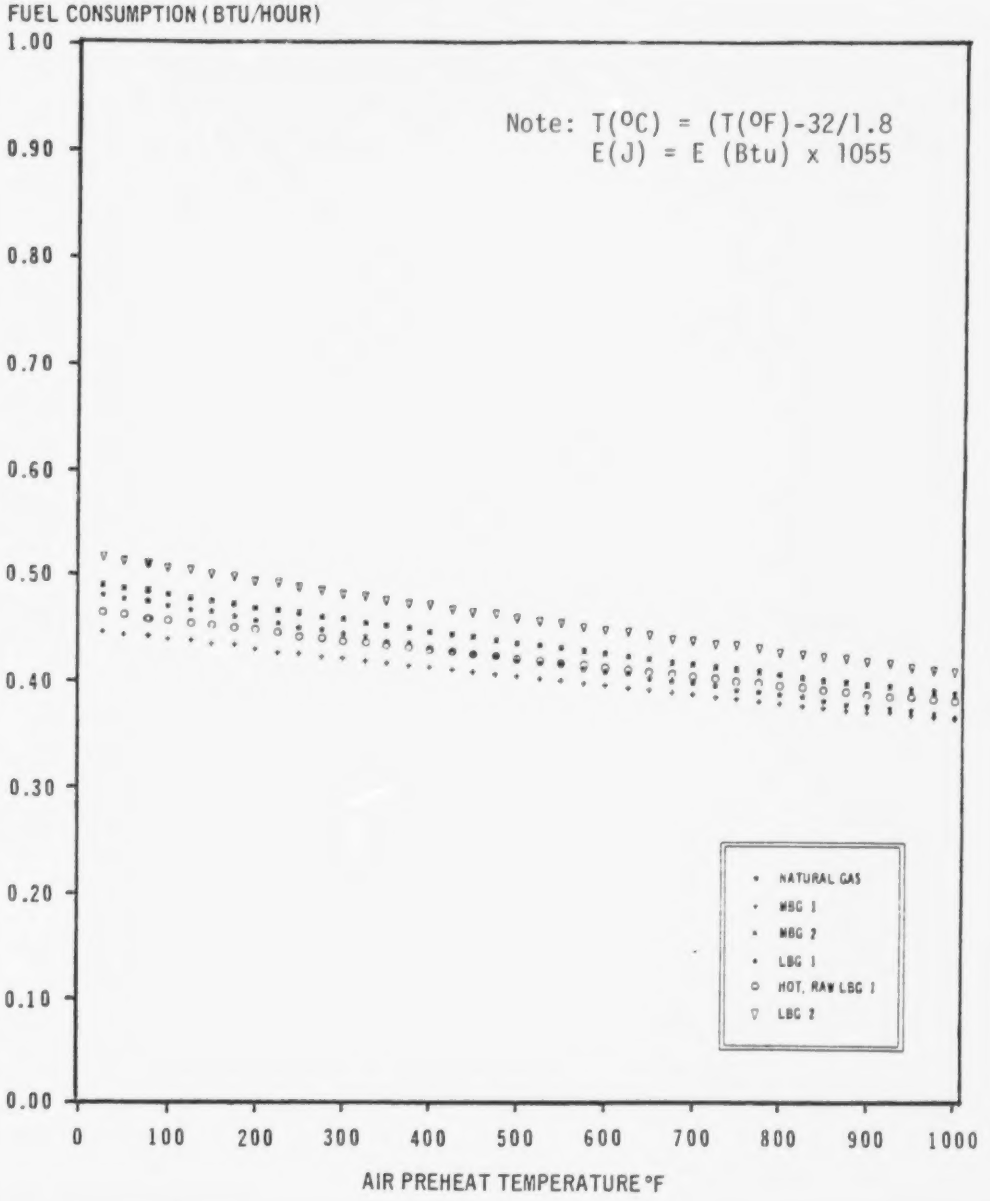

Figure 45. Furnace fuel consumption versus air preheat temperature for 540°C (1000°F) furnace with 15% excess air.

by the following two competing reactions:

(1) $XN + Y \rightarrow NO + \ldots$(oxidation)

(2) $XN + Z \rightarrow N_2 + \ldots$(reduction),

where XN characterizes nitrogen compounds like HCN, $NH_3$, and NCO, which are formed due to volatilization of the nitrogen containing solid or liquid fuel. Y species (e.g. HO, $HO_2$, O) are dominant in the fuel-lean, or oxygen-rich, region of the flame and Z species (e.g. NO, NH) are dominant in the fuel-rich region of the flame.

Thermal $NO_x$ reactions are slower than the combustion reactions and estimations of thermal $NO_x$ emissions can be made with reasonable accuracy without taking into account the specific combustion kinetics. In this report, estimation is based on the classical Zeldovich reaction mechanism. However, thermal $NO_x$ estimation will represent total $NO_x$ only for gaseous fuels and for liquid fuels like distillate oils which contain negligible amounts of chemically-bound nitrogen (0.1 percent by weight).

The concern of this chapter is mainly with the increasing $NO_x$ emissions due to the formation of thermal $NO_x$ from the addition of heat recovery devices. The increasing air preheat leads to a higher flame temperature. $NO_x$ formation gradually increases up to 1800 °C, while beyond this temperature a rapid linear increase is observed and $NO_x$ formation reaches a maximum at 1950 °C.[1/] Typically, flame temperatures rise from 1600 °C to approximately 1800 °C due to a 500 °C increase in combustion air temperature. This will substantially increase the thermal $NO_x$ emissions. Although changes in fuel $NO_x$ emissions depend on fuel type and not on changes in air preheat, there is considerable evidence indicating a decrease in percent conversion of fuel-bound nitrogen with increasing air preheat.[2/] However, the effect of temperature on the conversion of fuel nitrogen is much smaller than the corresponding effect on conversion of atmospheric nitrogen. Therefore, fuel $NO_x$ emissions are not addressed in this chapter. However, some references on fuel $NO_x$ emissions estimation are listed in Appendix F.

The majority of the chapter focuses on the model developed to estimate thermal $NO_x$ emissions from combustors, specifically thermal NO which constitutes 90 to 95 percent of thermal $NO_x$ emissions, as well as $NO_x$ emission estimates for different degrees of combustion air preheat in a natural gas-fired combustor. The chapter also describes the actual effect of air preheat on $NO_x$ emissions.

## 6.2 THERMAL $NO_x$ MODEL

A simple thermal NO formation model was developed in which the amount of NO formed depended upon the temperature profile, the concentration profiles of reactants, and the residence time in the combustor. This model assumes one dimensional homogenous plug flow of combustion gases along the length of a combustor and the temperature was assumed to vary only along the combustor length.

The NO kinetics were based upon the Zeldovich reaction mechanism.[3]

$$(1)\quad O_2 + [M] \underset{k_{-1}}{\overset{k_1}{\rightleftarrows}} 2\,[O] + [M]$$

$$(2)\quad [O] + N_2 \underset{k_{-2}}{\overset{k_2}{\rightleftarrows}} NO + [N]$$

$$(3)\quad [N] + O_2 \underset{k_{-3}}{\overset{k_3}{\rightleftarrows}} NO + [O]$$

where [M] is any free radical

[O] is free radical oxygen

[N] is free radical nitrogen

Generally, it is accepted that atomic oxygen and molecular nitrogen reach equilibrium before NO formation becomes important.[4] Under this condition, the rate expression for NO formation to the Zeldovich mechanism can be simplifies to read:

$$\frac{d[NO]}{dt} = \left\{ \frac{k_1}{k_{-1}} \quad [O_2]^{\frac{1}{2}} \right\} \left\{ \frac{2k_2k_3[N_2]\ [O_2] - 2k_{-2}k_{-3}[NO]^2}{k_{-2}[NO] + k_3\ [O_2]} \right\}$$

This rate expression was integrated with respect to time in order to obtain the amount of NO formed in the combustor. The values of the rate constants are given in Table 32.

The NO kinetics model described above was applied to the natural gas combustion data developed by the Institute of Gas Technology (IGT) under a Department of Energy (DOE) contract.[5] The data in Table 33 were collected on an experimental IGT furnace burning natural gas from a forward flow burner similar to those used in steel reheat furnaces. The temperature profiles in the furnace under the conditions given in Table 33 and as measured by IGT are given in Figure 46.

## TABLE 32. KINETIC CONSTANTS FOR NO FORMATION

$$k_n = a_n T^{bn} \exp(-E_n/T)$$

| Rate Constant* | $a_n$ | $b_n$ | $E_n$ | $k_n$ units |
|---|---|---|---|---|
| $k_1$ | $5.5 \times 10^{17}$ | -0.5 | 59,700 | $cm^3 . mole^{-1} . sec^{-1}$ |
| $k_{-1}$ | $2.2 \times 10^{16}$ | -0.5 | 0 | $(cm^3 . mole^{-1} . sec^{-1})^2$ |
| $k_2$ | $7.0 \times 10^{11}$ | +0.5 | 38,446 | $cm^3 . mole^{-1} . sec^{-1}$ |
| $k_{-2}$ | $1.33 \times 10^{11}$ | +0.5 | 0 | $cm^3 . mole^{-1} . sec^{-1}$ |
| $k_3$ | $2.40 \times 10^{11}$ | +0.5 | 3,321 | $cm^3 . mole^{-1} . sec^{-1}$ |
| $k_{-3}$ | $5.0 \times 10^{10}$ | +0.5 | 19,424 | $cm^3 . mole^{-1} . sec^{-1}$ |

---

*The data for rate constants are obtained from Reference 6.

## TABLE 33. IGT NATURAL GAS CONSUMPTION DATA*

| | |
|---|---|
| Fuel Flow | 146 SCM/hr. |
| Air Flow | 1528 SCM/hr. |
| Air Preheat Temperature | 340°C |
| Flame Length | 180 cm |
| Furnace Length | 425 cm |
| Furnace Cross Section | 140 x 140 $cm^2$ |
| Flue gases | 1671 SCM/hr. |
| Flue Gas Temperature | 1334°C |
| $CO_2$ in Flue Gases | 10.9% (dry basis) |
| $O_2$ in Flue Gases | 2.0% (dry basis) |
| $N_2$ in Flue Gases | 87.0% (dry basis) |
| $NO_x$ in Flue Gases | 300 ppm |

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*Data was obtained from Reference 5.

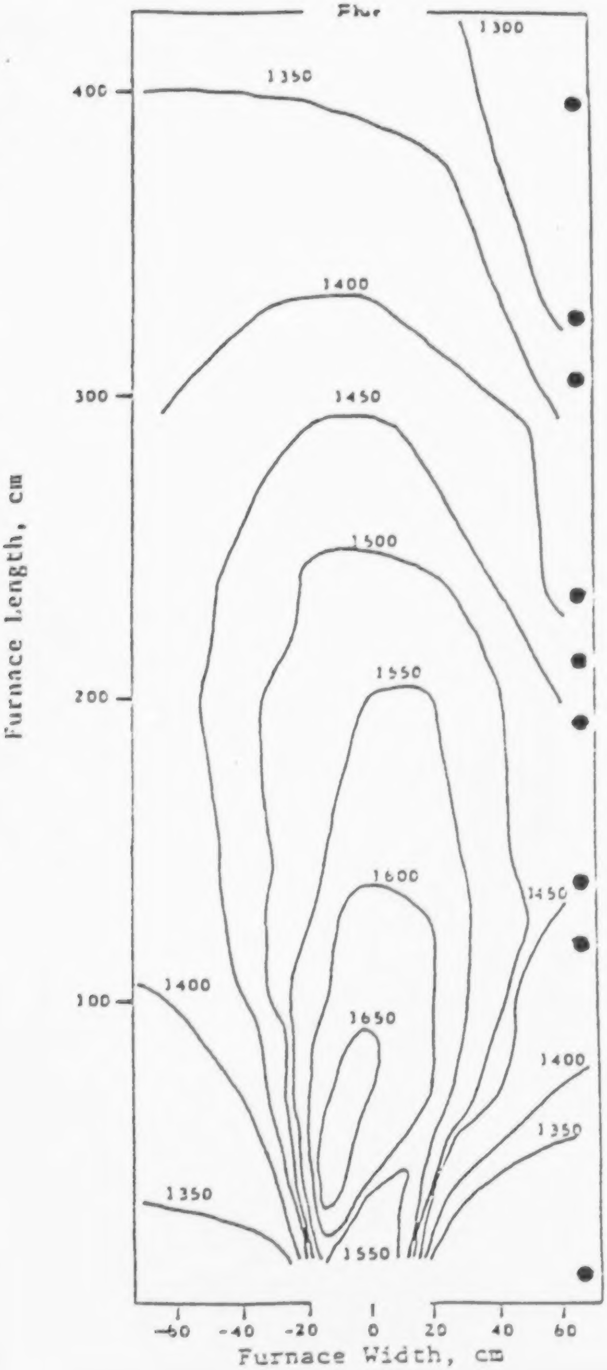

Figure 46. Isothermal profiles in the IGT furnace (°C).

The isotherm profiles in Figure 46 were converted into a simple unidirectional profile with respect to residence time in the furnace as shown in Figure 47. The mole fractions of nitrogen at the furnace entrance and at the exit are about the same. However, the mole fraction of oxygen changes from about 0.192 at entrance to about 0.018 at exit. All the combustion reactions are completed at the point where the flame ends and, if it is assumed (due to lack of data on combustion kinetics) that oxygen concentration drops linearly with distance during combustion, an oxygen concentration profile will be obtained (see Figure 47 ).

A computer program was developed to calculate thermal $NO_x$ formation according to the rate expression given previously. The residence time of combustion gases in the furnace was calculated from the average linear velocity of the combustion gases in the combustor. This residence time was the upper limit for the integration of the NO rate expression.

The input to the computer program consists of temperature and concentration profile data for the furnace. The amount of NO formed as calculated by this program under the conditions given in Table 33 is 286 ppm, within five percent of the experimentally measured value of 300 ppm. However, the data on NO formation given in the IGT report for Koppers-Totzek oxygen gas* is 112 ppm, as calculated by this program, which is considerably lower than the experimentally observed value of 290 ppm.

## 6.3 EFFECTS OF COMBUSTION AIR PREHEAT ON $NO_x$ EMISSIONS

Preheating combustion air increases the flame temperature and heat radiation from the combustor flame and it also reduces the amount of energy lost with the final flue gases. This enables fuel consumption to be reduced. However, the reduction in fuel flow and the corresponding reduction in air flow leads to an increase in the residence time in the combustor. The thermal NO production may increase due to an increase in the flame temperature as well as residence time.

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* Koppers-Totzek oxygen gas is a medium-Btu gas produced from coal.

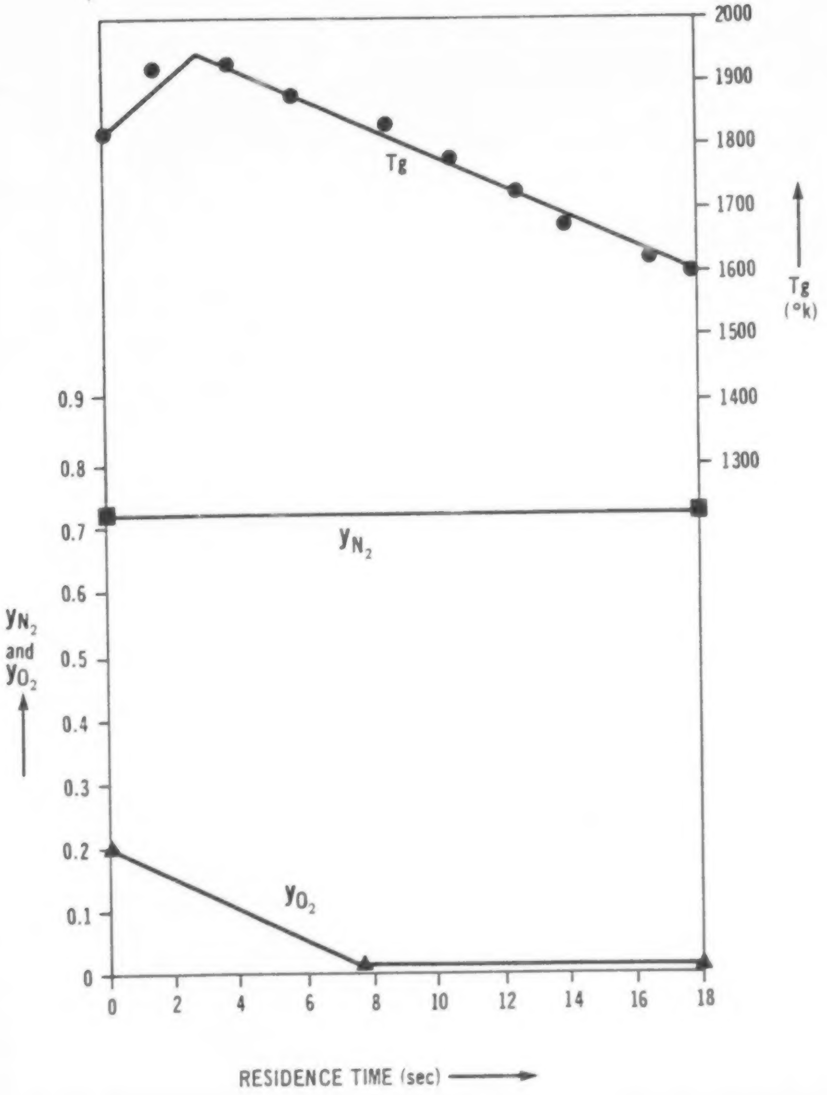

Figure 47. Temperature and concentration profiles in the IGT furnace.

The residence time data for natural gas listed in Table 34 for different air preheat temperatures were calculated from an energy conservation model of a furnace developed by EEA. The adiabatic flame temperatures in Table 34 were obtained from a personal communication with Mr. Richard Reed of North American Manufacturing Company.

These data were applied to the IGT furnace and burner described previously in this chapter. The fuel flow and air flow data in Table 35 are hypothetical and were calculated from the residence time data of Table 34. In order to project thermal $NO_x$ emissions for different degrees of air preheat, it was necessary to make the following assumptions, due to lack of real data:

- The flame length is the same for all the cases (viz., 180 cm) and the peak temperature occurs at the same point in the furnace for all the cases (viz., at 60 cm from the burner end of the furnace).
- The temperature at the burner end of the furnace is 100°C below the peak temperature and the temperature at the flue gas exit end of the furnace is 350°C below the peak temperature. This assumption is in line with the observed temperature profile for natural gas as shown in Figure 46.

The temperature and concentration profiles for cases 1, 4, and 7 of Table 34 are plotted with respect to furnace length in Figure 48. The $NO_x$ emission results calculated for different air preheat temperatures are listed in Table 35 and plotted in Figure 49. Below 540°C air preheat temperature, thermal NO formation is not significant.*

## 6.4 LIMITATIONS OF MODEL

The amount of NO formation as calculated by this model will be as close to reality as the temperature profile estimates are. However, there are four important limitations of this model:

- It does not take into account the effect of backmixing of combustion gases and the resulting increase in residence time. This limitation may cause the NO formation calculated by this model to be less than the actual amount.
- It does not take into account the temperature and concentration variation in a 3-dimensional space.
- The atomic oxygen equilibrium assumption of this model may be invalid. The NO levels which were calculated generally are lower than the measured NO levels in furnaces and combustors.

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* As calculated by this model, $NO_x$ emissions are only 66 ppm at 430°C air preheat.

## TABLE 34. AIR PREHEAT DATA FOR NATURAL GAS

| SR NO | Air Preheat Temperature (10% Excess Air) °C (°F) | Residence Time Relative to 316°C Residence Time | Peak Temperature (80% of adiabatic Flame temperature) °C (°F) |
|---|---|---|---|
| 1. | 320 (600) | 1.0 | 1557 (2834) |
| 2. | 430 (800) | 1.1 | 1591 (2895) |
| 3. | 540 (1000) | 1.2 | 1567 (2954) |
| 4. | 650 (1200) | 1.32 | 1654 (3009) |
| 5. | 760 (1400) | 1.43 | 1683 (3061) |
| 6. | 980 (1800) | 1.54 | 1710 (3110) |
| 7. | 980 (1800) | 1.64 | 1736 (3156) |

Natural Gas Composition:

| | |
|---|---|
| $CH_4$ | 90% by Volume |
| $C_2H_6$ | 5% by Volume |
| $N_2$ | 5% by Volume |

Flue Gas Composition:

| | |
|---|---|
| $CO_2$ | 8.77% by Volume |
| $H_2O$ | 17.09% by Volume |
| $O_2$ | 1.73% by Volume |
| $N_2$ | 72.41% by Volume |

## TABLE 35. EFFECTS OF COMBUSTION AIR PREHEATING ON $NO_X$ EMISSIONS

| SR. NO. | Fuel Flows (SCM/hr) | Air Flow (10% Excess) (SCM/hr) | Air Preheat Temperature, °C(°F) | Peak Temperature in Furnace (°K) | Residence Time (SEC) | NO* (wet basis) (ppm) | NO g/GJ(lb/MMBtu) |
|---|---|---|---|---|---|---|---|
| 1. | 146.0 | 1510 | 320 | 1830 | 18.18 | 35 | 21 (0.051) |
| 2. | 121.7 | 1259 | 430 | 1897 | 21.82 | 166 | 104 (0.241) |
| 3. | 113.2 | 1259 | 540 | 1927 | 24.00 | 326 | 204 (0.474) |
| 4. | 112.3 | 1056 | 650 | 1956 | 26.00 | 601 | 375 (0.873) |
| 5. | 94.81 | 980.8 | 760 | 1983 | 28.00 | 1024 | 640 (1.489) |
| 6. | 89.02 | 921.0 | 980 | 2009 | 29.81 | 1620 | 1012 (2.354) |

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*Basis: 1.73% oxygen in flue gases.

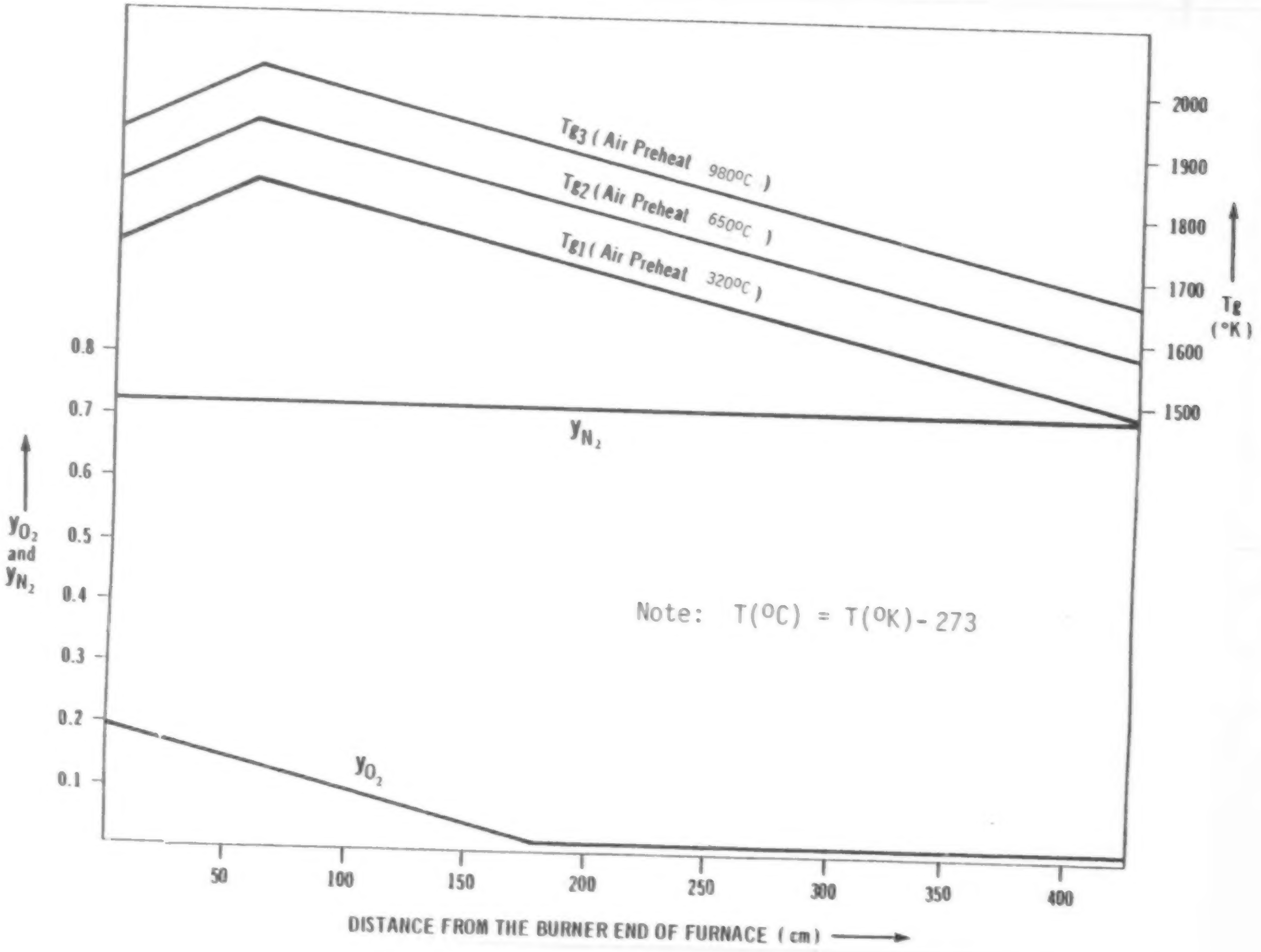
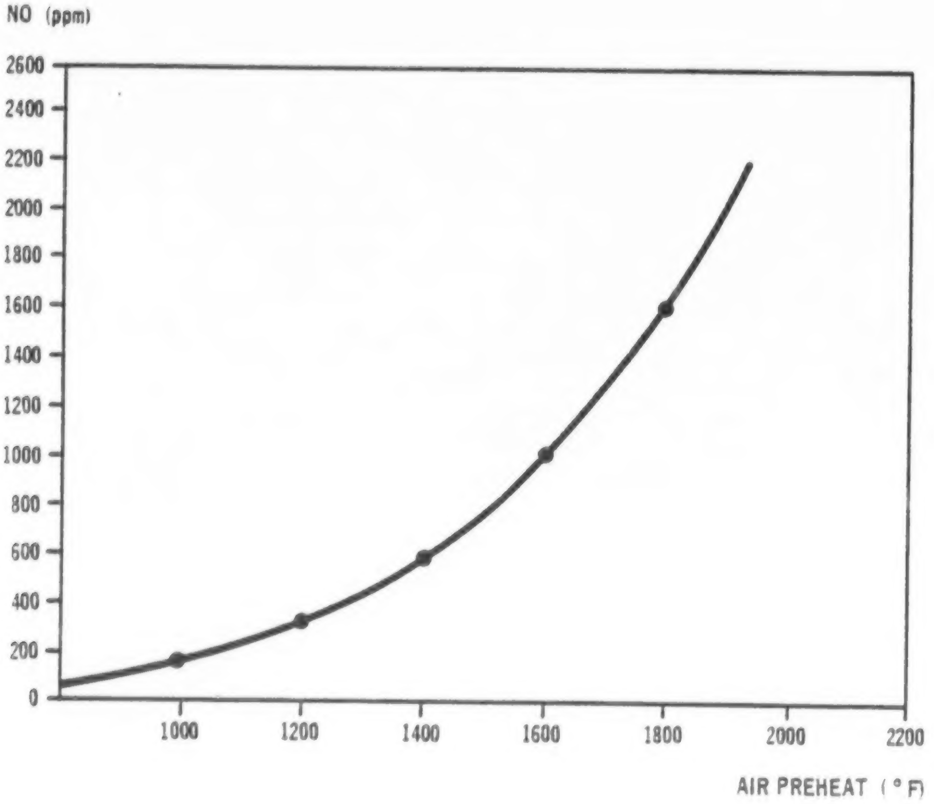


Figure 48. Temperature and concentration profiles for natural gas combustion.



Note: T(°C) = (T(°F)-32)/1.8

Figure 49. Effect of combustion air preheating on $NO_x$ emissions.

- **Because of superequilibrium oxygen atom concentrations, rates of formation of NO can be higher by an order of magnitude than those calculated for equilibrium conditions.[87]**

## 6.5 CONCLUSION

Sulfur dioxide and particulate emissions will be reduced as a result of reduced fuel consumption associated with waste heat recovery. In the case of combustion air preheat in gas furnaces, reductions in emissions of these pollutants could be up to 20% if preheated air temperatures are on the order of 540°C (1000°F).

There is little effect of combustion air preheat on fuel $NO_x$ formation; other studies have found that a small decrease in fuel $NO_x$ occurs with increase in combustion air temperature and reduced fuel consumption. This decrease is usually small in absolute magnitude compared to changes in thermal $NO_x$ with combustion air temperature.

There is only a gradual increase in thermal $NO_x$ with increasing flame temperature up to 1790°C (3250°F). Above this flame temperature, thermal $NO_x$ formation increases rapidly and approximately linearly with temperature up to about 1950°C (3550°F), where it reaches a maximum. However, most furnaces and boilers do not operate at air preheat temperatures which result in such high flame temperatures. Combustion air temperatures must be well above 540°C for flame temperatures of 1750°C to be reached. Therefore, it is not expected that the increases arising from combustion air preheat will generally cause $NO_x$ emission increases of over 100 ppm to occur. The exception will be those industries with process temperatures at or above 1370°C (2500°F).

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# APPENDIX A

## BURNER AVAILABILITY FROM VENDORS*

As a part of EEA's investigation into the availability of burners capable of firing with high temperature preheated air, a number of burner manufacturers were queried as to their current work in this area. Four companies responded that they actively were involved in the high temperature combustion market and furnished EEA with information on their products. These companies were Hotwrok, Inc., Lexington, Kentucky; North American Manufacturing, Cleveland, Ohio; Bloom Engineering Company, Inc., Pittsburgh, Pennsylvania; and Hauck Manufacturing Company, Lebanon, Pennsylvania.

### HOTWORK, INC.

At present, Hotwork, Inc. has not done any burner work for systems using preheated air at temperatures greater than 1400°F. The reason for this, according to John Newby, Director of Research, is that they have not been given any commissions in this area. Hotwork, however. does have a line of self-recuperative burners in sizes from 0.5 MMBtu/hr to 2.5 MMBtu/hr that are capable of generating and firing at temperatures over 1800°F. These burners currently are available with type 1 (North American classifications used throughout) flames and they are experimenting with type 8 flames.

The following is a list of commissions that Hotwork, Inc. would accept in the area of high temperature combustion.

| | Time | Flame Types | Preheat | Comment |
|---|---|---|---|---|
| 1) | Current | #'s 1, 2 | 1600-1700°F | could make |
| 2) | Current | #'s 3, 4 | 1600-1700°F | would suggest other flame types |
| 3) | Current | #5 | N/A | limited application technically feasible |

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*The data and calculations presented in this and other appendices represents primary source information. Since they were obtained in English units, they are presented in those units.

| | | | |
|---|---|---|---|
| 4) Current | #'s 6, 7 | 1600-1700°F | poor flame: could make out; would suggest others |
| 5) Current | # 8 | 450-600°F | material problems in exceeding these temperatures; currently working on this; |
| 6) Future | # 8 | | have type for high preheat greater than 1400°F |

## NORTH AMERICAN

North American Manufacturing currently offers five burner models for use with high temperature combustion. According to Richard Reed, Director of Technical Information, a significant number of North American burners can operate at low levels of preheated air. Further information is available from the company. Table A-1 gives the five burners suggested by North American for use with high temperature combustion air.

## BLOOM ENGINEERING

Bloom Engineering currently is involved in high temperature work both in the U.S. and in Europe. As of the date of this paper, Bloom has penal-shaped, short, clear flame; long, luminous flame; and radial "high thermal release" flame burners -- all installed and operating at preheat air temperatures of 1200°F.

John E. Johns, Vice President of Sales, said that Bloom would be willing to accept commissions for all flame types at preheat temperatures up to 1800°F for burners ranging in size from 1 to 100 million Btu/hr. Bloom burners can be used with most industrial fuels including blast furnace, coke oven, LP and natural gases, No. 2 and No. 6 oils, and tar. Typical applications generally are steel mill oriented with some boiler applications included.

Franklin Miller, an engineer for Bloom, thinks that the lack of quality recuperator equipment is the major reason behind the low preheat temperatures currently generated by waste heat recovery systems. Preheat temperatures at burners also may be 200 to 300°F less than recuperator ratings due to leaks and heat losses through piping even when insulation is used.

## HAUCK MANUFACTURING

Hauck Manufacturing has tested a substantial portion of its product line on preheated air. The following products are capable of using preheated air at temperatures of up to 900°F.

| TYPE | NOZZLE MIX | HIGH VELOCITY | HIGH VELOCITY | RADIANT TUBE |
|---|---|---|---|---|
| Name: | NMC Series Combination Fuel-Fired | Temperature High Velocity<br>Temperature Medium Velocity<br>Low Capacity Burners | Enerjet | RTC Series Dual-Fuel |
| Preheat: | 800°F | 700°F | | 800°F |
| Fuels: | any clean fuel like No. 6 | most gases or No. 2 oil | clean gas or No. 2 oil | clean gas or No. 2 oil |
| Excess: | max. 700°F | max. 150% Gas, oil | max. 360% Gas, oil | min. 10% Gas, oil |
| | max. 500% | | max. 500% oil | min. 15% oil |

| TYPE | NOZZLE MIX | HIGH VELOCITY | HIGH VELOCITY | RADIANT TUBE |
|---|---|---|---|---|
| Size: (Btu/hr) | 183,000-16,283,000 | 30,000-200,000 | 437,000-3,621,000 | 240,000-1,159,000 |

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## TABLE 36. NORTH AMERICAN MFG. CO. - BURNERS FOR USE WITH PREHEATED COMBUSTION AIR

| Burner Series No.: | 6816 | 6819/6819A | 6820A/6820C | 6825 | 6828 |
|---|---|---|---|---|---|
| Burner Description: | w/ individually adjusted vanes | basic large burner | w/ provision for pilot, obs. port flame monitor | small size | flat flame |
| Air Pipe Size Range: | 14"-20" | 2"-24" | 6"-24" | 3"-6" | 3"-6" |
| Max. Air Temp.,°F* | 1100 | 1100 | 1100 | 1100 | 1100 |
| Flame Type(s)**: | 1 or 6 adjustable | 6 for 6819<br>1 for 6819A | 6 for 6820C<br>1 for 6820A | 1 | 5 |
| Typical Applications[†]: | soaking pits | steel-reheat furnaces,<br>tunnel kilns | aluminum reverbs, glass melters | small reverbs,<br>unit melters | cover annealers,<br>reheat soak zones |
| MMBtu/hr at Max. Preheat: | 10.6-21.5 | 0.9-28.7 | 1.9-31.0 | 0.5-1.9 | 0.5-1.9 |
| Turndown Ratio: | 5:1 | 5:1 | 6820A - 5:1<br>6820C - 3:1 | 6:1 | 6:1 |
| Construction Materials[‡]: | alloy disc w/refr. face | | alloy disc w/refr. face | refr. disc | alloy disc |
| Fuels: | gas<br>No. 2, No. 6 oils | gas<br>No. 2, No. 6 oils | gas<br>No. 2, No. 6 oils | gas<br>No. 2 oil | gas<br>No. 2 oil |

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*North American has many other burner types that may not have been designed for hot air but can be used with 500-700°F air in some circumstances.

**Approximately as per classification on p. 234 of North American Combustion Handbook, 2nd Edition.

[†] All burners are adaptable to a variety of applications.

[‡] All burners have refractory insulation lining on the inside surface of the outers walls of the air plenum.

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# APPENDIX B

## FUEL SAVINGS CALCULATION DERIVATION

The amount of fuel which is saved by preheating the combustion air can be calculated using the first law of thermodynamics. Figure B-1 shows the energy mass balances across the furnace. By using the energy and mass balances for the furnace system, the percentage of fuel savings can be calculated.

Two furnace systems are considered:

CASE A furnace system using combustion air without air preheat.

CASE B furnace system using combustion air with air preheat.

The production rate and the furnace and flue gas temperatures are assumed to be the same in both cases.

The energy balance for these two cases is given by:

CASE A $$Q_f + Q_a = Q_g + Q_l + Q_p \qquad (1)$$

CASE B $$Q'_f + Q'_a = Q'_g + Q'_l + Q'_p \qquad (2)$$

where $Q_f$ = rate of energy input from the fuel combustion

$Q_a$ = rate of enthalpy input from combustion air

$Q_g$ = rate of enthalpy input from the flue gases

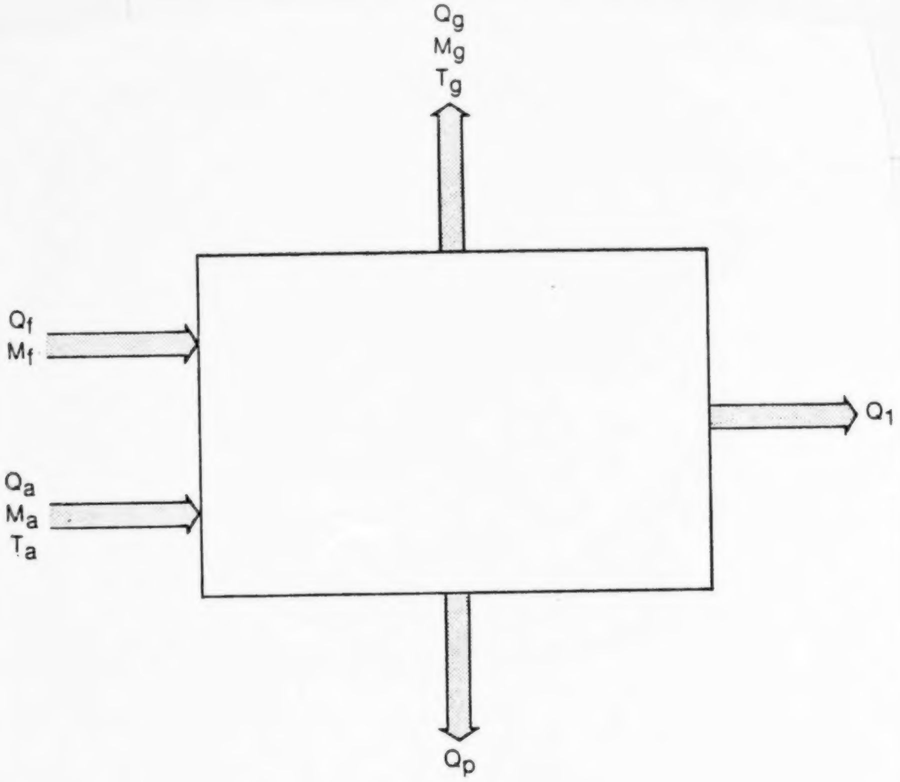
$Q_l$ = rate of energy loss from the furnace system through walls, etc.

$Q_p$ = rate of energy input to the product

(Primes denote CASE B values)

Since the production rate of both cases is the same, $Q_p = Q'_p$, and it is the temperature which is controlled, the energy loss from each furnace also can be considered equivalent, $Q_l = Q'_l$. Thus, the energy flow of the products and losses for both cases are constant and equal:

$$Q_l + Q_p = Q'_l + Q'_p = Q_c \qquad (3)$$



$Q_f$ = energy input from fuel combustion
$Q_g$ = enthalpy of the flue gases
$Q_a$ = enthalpy of the combustion air
$Q_1$ = energy loss of the furnace system
$Q_p$ = energy into the product
$M_f$ = mass flow of fuel
$M_g$ = mass flow of flue gas
$M_a$ = mass flow of combustion air
$T_g$ = temperature of the gas
$T_a$ = temperature of the air

Figure 50. Energy and mass flow balance of furnace system.

Equations 1 and 2 are now written in terms of equation 3.

$$Q_c = Q_f + Q_a - Q_g \tag{4}$$

$$Q_c = Q'_f + Q'_a - Q'_g \tag{5}$$

Next, the individual mass flows in the combustion process are described. The mass flow of the combustion air and flue gas can be expressed as functions of the mass flow of the fuel, the air/fuel ratio for the fuel used, and the amount of excess air used in the furnace system.

$$M_a = AF(1+E)M_f \tag{6}$$

$$M_g = M_f + M_a = [AF(1+E)+1]M_f \tag{7}$$

where $M_a$ = mass flow of combustion air

$M_g$ = mass flow of flue gas

$M_f$ = mass flow of fuel

$AF$ = air/fuel ratio

$E$ = fraction excess air

The energy flows of the fuel, air, and flue gas now can be expressed as a function of mass flows using equations 6 and 7:

$$Q_f = (LHV)M_f \tag{8}$$

$$Q_a = Cp_a T_a M_a = Cp_a T_a [AF(1+E)M_f] \tag{9}$$

$$Q_g = Cp_g T_g M_g = Cp_g T_g [1+AF(1+E)]M_f \tag{10}$$

where $LHV$ = lower heating value of the fuel

$Cp_a$ = specific heat of the air

$Cp_g$ = specific heat of the gas

$T_a$ = temperature of the air

$T_g$ = temperature of the gas

Equations 4 and 5 now are expressed in terms of equations 8, 9, and 10.

$$Q_c = (LHV)M_f + Cp_a T_a [AF(1+E)M_f] - Cp_g T_g [1+AF(1+E)]M_f \tag{11}$$

$$Q_c = (LHV)M'_f + Cp'_a T'_a [AF(1+E)M'_f] - Cp_g T_g [1+AF(1+E)]M'_f \tag{12}$$

where it is assumed that $T_g = T'_g$, because the furnace is temperature controlled.

The reduced fuel consumption ($M'_f$) is found by equating 11 and 12.

$$M'_f = \frac{\left|LHV + Cp_a T_a[AF(1+E)] - Cp_g T_g[1+AF(1+E)]M_f\right|}{\left|LHV + Cp'_a T'_a[AF(1+E)] - Cp_g T_g[1+AF(1+E)]\right|} \qquad (13)$$

The percentage of fuel savings (FS%) is given by:

$$(FS\%) = 1 - \left|\frac{LHV + Cp_a T_a[AF(1+E)] - Cp_g T_g[1+AF(1+E)]}{LHV + Cp'_a T'_a[AF(1+E)] - Cp_g T_g[1+AF(1+E)]}\right| \times 100 \qquad (14)$$

Equation 14 was used to calculate fuel savings for a furnace system burning No. 2 oil and operating at 15 percent excess air. Table B-1 is the fuel savings obtained for various flue gas and air preheat temperatures. Figure B-2 is a graph of these results.

## TABLE 37. FUEL SAVINGS (%) FOR $T_{ph}$ and $T_{fg}$, 15% EXCESS AIR, NO. 2 OIL

| $T_{fg}$ ($^{o}$F) | $T_{ph}$ ($^{o}$F) | | | | | |
|---|---|---|---|---|---|---|
| | 400 | 600 | 800 | 1000 | 1200 | 1400 |
| 1400 | 9.7 | 14.9 | 19.7 | 24.0 | 28.0 | 31.7 |
| 1600 | 10.5 | 16.1 | 21.2 | 25.8 | 30.0 | 33.7 |
| 1800 | 11.6 | 17.6 | 22.9 | 27.8 | 32.1 | 36.1 |
| 2000 | 12.8 | 19.3 | 25.1 | 30.2 | 34.7 | 38.8 |
| 2200 | 14.4 | 21.5 | 27.7 | 33.1 | 37.8 | 42.0 |
| 2400 | 16.4 | 24.3 | 31.0 | 36.7 | 41.6 | 45.9 |
| 2600 | 19.2 | 27.9 | 35.1 | 41.2 | 46.3 | 50.6 |
| 2800 | 23.1 | 32.9 | 40.7 | 47.0 | 52.2 | 56.5 |

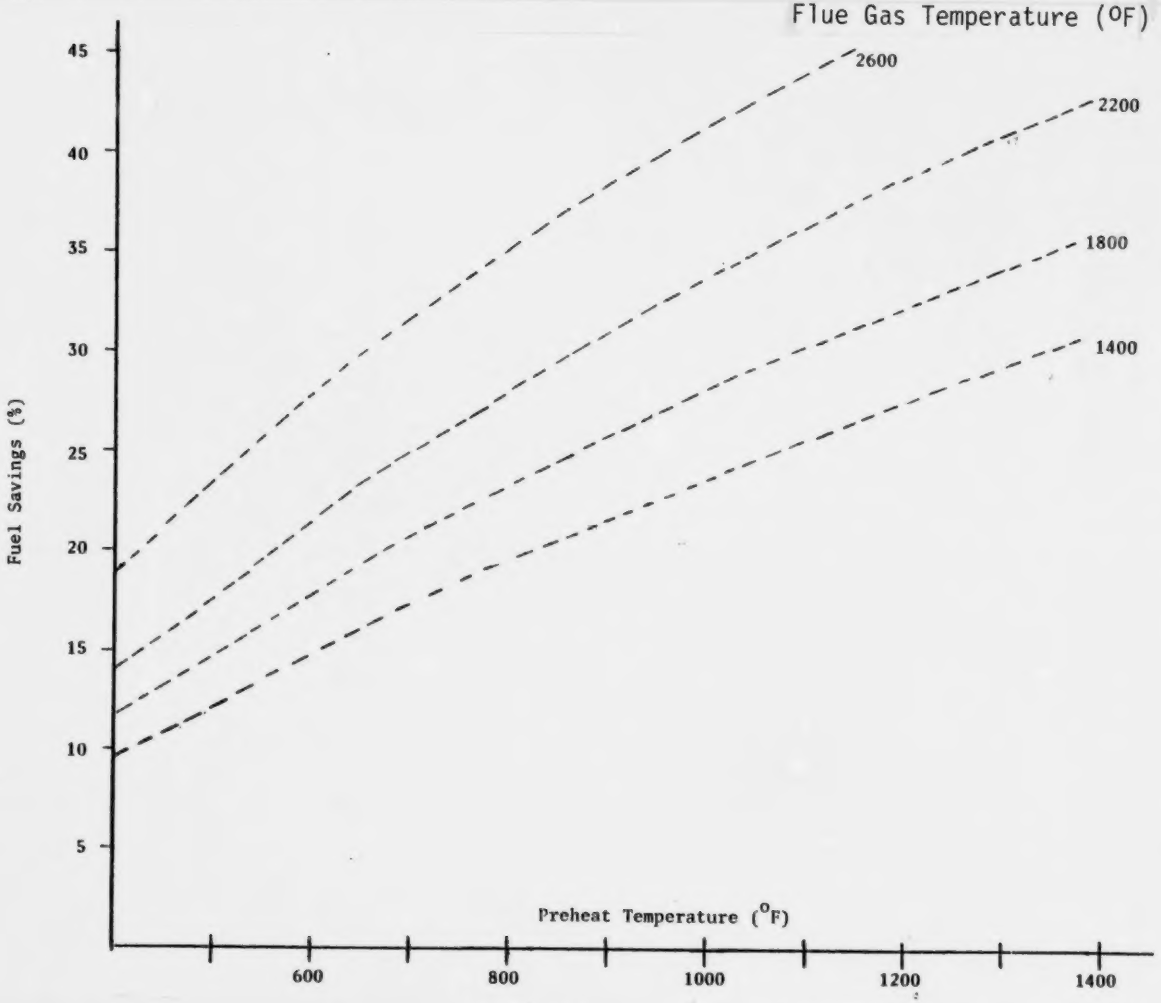


Figure 51. Fuel savings versus Tph for selected Tfg, 15% E.A., #2 oil.

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## APPENDIX C

## MODELING HEAT TRANSFER IN RECUPERATORS

Manufacturers of air recuperators estimate the selling price of their products based on a function of recuperator area and construction materials. It became necessary to be able to predict required heat exchanger surface area, which can be accomplished by using basic heat transfer analyses.

### Convection Recuperator

The average heat transfer rate in a parallel or counterflow heat exchanger is given by:

$$\dot{Q} = \bar{U}A\Delta T_{1m} \qquad (1)$$

where $\dot{Q}$ = heat transfer, Btu/hr

$\bar{U}$ = overall heat transfer coefficienct, Btu/(hr)(ft$^2$)(°F)

$A$ = exhanger area, ft$^2$

$\Delta T_{1m}$ = log mean temperature difference

$$\frac{T_{h\ in} - T_{c\ out} - T_{h\ out} - T_{c\ in}}{\ln\left(\frac{T_{h\ in} - T_{c\ out}}{T_{h\ out} - T_{c\ in}}\right)} \qquad (2)$$

where $T_{h\ out}$ = temperature of flue gas out of recuperator, °F

$T_{c\ in}$ = temperature of air into recuperator, °F

$T_{h\ in}$ = temperature of flue gas into the recuperator, °F

$T_{c\ out}$ = temperature of air out of recuperator, °F

For a given heat exchanger, the heat transfer rate is known for a given set of flue gas and air temperature distributions. The overall heat transfer coefficient is calculable knowing the fluid dynamics and the primary modes of heat transfer. In this study convection and radiation units were examined.

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For a convection unit:

$$\bar{U}_{conv} = \frac{1}{\frac{1}{hgc} + \frac{L}{K} + \frac{1}{hac}} \qquad (3)$$

where hgc = convective heat transfer coefficient on flue gas side

L = length of recuperator

K = conduction heat transfer coefficient

hac = convective heat transfer coefficient on combustion air side

The wall resistance for a 5/16-inch stainless steel tube is 0.005(hr)$\cdot$(ft$^2$)($^o$F)/Btu which can be disregarded when compared to a value of 0.1(hr)$\cdot$(ft$^2$)($^o$F)/Btu for the convection term. Equation 3 can be simplified to be:

$$\bar{U}_{conv} = \frac{1}{\frac{1}{hgc} + \frac{1}{hac}} \qquad (4)$$

In a tube and shell recuperator, the combustion air usually flows inside the tubes. For turbulent flow inside a tube:

$$hgc = 0.023\ K\ D_i^{-0.2}\ \mu^{-0.8}\ \rho^{0.8}\ V_a^{0.8}\ Pr^{0.4} \qquad (5)$$

$$V_a = \frac{\dot{M}}{A} = \frac{\dot{M}}{\rho \pi r^2} \qquad (6)$$

The physical properties are based on the average temperature of the air

where $\dot{M}$ = air mass flow rate

$D_i$ = inner diameter

$\mu$ = viscosity

$\rho$ = density

$V_a$ = air velocity

Pr = Prandtl Number

As previously described in the text, the hot flue gases were chosen to flow counter to the combustion air on the outside of the tubes. To determine heat transfer correlations for this regime, one needs to know the number of tubes, number of rows, size of tubes, and space between rows.

The equation used for calculating the heat transfer coefficient for flow outside of the tubes depends on the term:

$$\frac{G_{max}\ D_o}{\dot{M}_b} = \frac{\dot{M}\ D_o}{nA_{min}\mu b} \tag{7}$$

where $n$ = number of rows

$A_{min} = (S_t - D_o)$(Length of tube)

$S_t$ = transverse space between tube

$D_o$ = outer diameter of tube

if $\frac{G_{max}\ D_o}{\mu b} < 6000$, use equation 8

if $\frac{G_{max}\ D_o}{\mu b} \geq 6000$, use equation 9

$$j = \frac{hc}{C_p G_{max}} Pr_b^{2/3} \left\{\frac{\mu_s}{\mu_b}\right\}^{0.14} \tag{8}$$

$$\frac{h_c D_o}{k_f} = 0.33\ C_H \left\{\frac{G_{max} D_o}{\mu_f}\right\} 0.6\ Pr^{2/3} \tag{9}$$

where $j$ = value is found from a curve[1/]

and subscripts

$s$ = surface

$f$ = film

$b$ = bulk

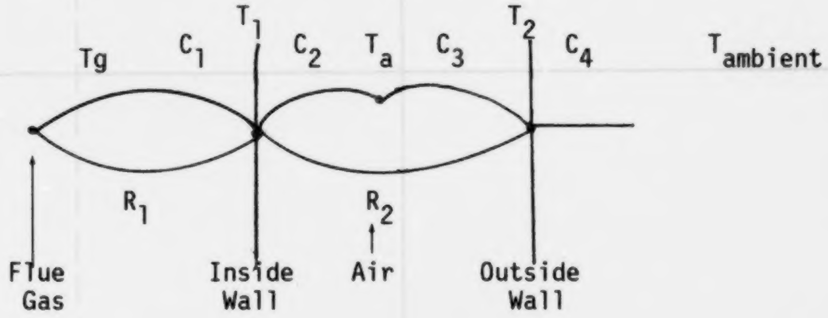
$C_H = 1.0$

This calculation was done by taking examples where the mass flow and construction were known to get the ranges of values for the parameters. It was found that equation 7 was always greater than 6000.

The overall heat transfer coefficient fell in the range of 5-10 Btu/ (hr)($ft^2$)(°F) and a value of $\bar{U}$ = 7.0 Btu/(hr)($ft^2$)(°F) was chosen for this study because it most consistently represented the actual applied cases.

## Radiation Unit Analysis

The heat transfer flow paths for a double shell radiation recuperator were modeled as follows:


$T_1$
$T_2$
Tg
$C_1$
$C_2$
$T_a$
$C_3$
$C_4$
$T_{ambient}$
$R_1$
$R_2$
Flue Gas
Inside Wall
Air
Outside Wall

where $C_1$ = convective heat transfer path

$R_1$ = radiative heat transfer path

From this model, the heat transfer system would be:

$$\dot{Q}_{C1} + \dot{Q}_{R1} = \dot{Q}_{C2} + \dot{Q}_{C3} + \dot{Q}_{C4} \qquad (10)$$

$$\dot{Q}_{R2} = \dot{Q}_{C3} + \dot{Q}_{C4} \qquad (11)$$

$$h_{gc}\,(T_{gm} - T_1) + \overline{GS}(T_{gm}{}^4 - T_1{}^4) = h_{ac}(T_1 - T_{am}) + h_{ac}\,(T_2 - T_{am}) + h_{wc}(T_2 - T_{amb}) \qquad (12)$$

$$\sigma\overline{GS}'(T_1{}^4 - T_2{}^4) = h_{ac}(T_2 - T_{am}) + h_{wc}(T_2 - T_{am}) \qquad (13)$$

where $\overline{GS} = f_1(T_1, T_{gm})$

$\overline{GS}' = f_2(T_1, T_2)$

gm = mean flue gas temperature

am = mean air temperature

wc = wall convection coefficient

The expressions for variables in the above equations are given by:

$$\overline{GS} = \frac{1 - \frac{T_1^3}{T_{gm}^3}}{1 - \frac{T_1^4}{T_{gm}^4}} \left(\frac{1}{\varepsilon_{CO_2}} + \frac{1}{\varepsilon_{H_2O}} -1\right)^{-1} \tag{14}$$

$$h_{gc} = 0.0023 \; K \; D_{eff}^{-0.2} \mu^{-0.8} \rho^{\,0.8} V_a^{\,0.8} Pr^{\,0.4} \tag{15}$$

$$V_a = \frac{\dot{M}a}{\rho_{am}\pi(R_o^2 - r_1^2)} \tag{16}$$

$$\dot{M}_a = \frac{FR}{LHV} AF_{ST}(1+E) \tag{17}$$

$$D_{eff} = D_o - D_i \tag{18}$$

$$h_{ac} = 0.023 \; V_g^{0.8} D_i^{0.2} K \frac{\mu}{\rho}^{-0.8} Pr^{0.4} \tag{19}$$

$$V_g = \frac{\dot{M}_g}{\rho\pi r_1^2} \tag{20}$$

Solving equation 13 for $T_1^4$ yields:

$$T_1^4 = T_2^4 + T_2 \frac{h_{ac} + h_{wc}}{\sigma\overline{GS}'} - \frac{h_{ac}}{\sigma\overline{GS}'} T_{am} - \frac{h_{wc}}{\sigma\overline{GS}'} T_o \tag{21}$$

and rearranging equation 12:

$$T_1^4 + T_1 \frac{h_{gc} + h_{ac}}{\sigma\overline{GS}} + T_2 \frac{h_{ac} - h_{wc}}{\sigma\overline{GS}} - \frac{h_{ac}}{\sigma\overline{GS}} T_{gm} - T_{gm}^4 - \frac{2h_{ac}}{\sigma\overline{GS}} T_{am} \quad \frac{h_{wc}}{-\sigma\overline{GS}} T_o = 0 \tag{22}$$

This is a system of two equations with two independent variables, $T_1$ and $T_2$. The system can be solved by assuming a value of one variable, deriving the value of the other variable in the first equation and checking the results in the second equation until the solutions come within some error boundary.

This procedure was tried initially to model the whole unit, but the results were inconsistent and inaccurate. The proper choice of the average air and flue gas temperatures are critical to get acceptable results. It then was decided to do an iterative procedure over the length of the recuperator. The calculation was done for every 100°F change in the combustion air temperature, the result being given as needed recuperator lengths for a given diameter. The lengths then could be added to give a total recuperator length.

An error still remained in the calculation, but this error was a function of the firing rate and preheat temperature. It decreased monotonically with increasing firing rate and preheat temperature. (A possible explanation of the error is that for the smaller firing rate and lower preheat temperatures, the calculation step of 100°F was too large.) Normalization coefficients were derived and are shown in Table 38.

## TABLE 38. NORMALIZATION COEFFICIENTS

| FR - FIRING RATE MMBtu/hr | $T_{PH}$ - PREHEAT TEMPERATURE( $^{o}$F) | | |
|---|---|---|---|
| | 600 | 800 | 1000 |
| 15 | 1.25 | 1.10 | 1.08 |
| 30 | 1.15 | 1.05 | 1.02 |
| 60 | 1.12 | 1.02 | -- |

NOMENCLATURE:

$h$ = convective heat transfer coefficient

$K$ = conduction heat transfer coefficient

$\sigma$ = Boltzman constant

$\overline{GS}$ = gas surface radiation exchange parameter

$\varepsilon$ = emissivity

$\mu$ = viscosity

$Va$ = air velocity

$Pr$ = Prandtl number

$\dot{M}$ = mass flow rate

$FR$ = firing rate

$LHV$ = Lower Heating Value of fuel Btu/mole

$AF_{ST}$ = Stoichiometric air/flue ratio

$E$ = percent excess air

$D_o$ = outside tube diameter

$D_i$ = inside tube diameter

TABLE 38. NORMALIZATION COEFFICIENTS (continued)

SUBSCRIPTS:

a = air

am = mean air temperature

g = gas

gc = gas convection

gm = mean gas temperature

amb = ambient

wc = wall convection

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## REFERENCES

1. Keith, F., Principles of Heat Transfer, International Textbook Co., 1968, p. 422.

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## APPENDIX D

## THERMODYNAMIC FIRST LAW ANALYSIS OF A SYSTEM COMPRISING A FURNACE AND A FURNACE WITH A RECUPERATOR

The first law of thermodynamics keeps account of the energy flows in the system being studied. For the furnace the energy flows are the fuel and air in, the flue gas out, the energy delivered to the load, and assorted losses. Thermodynamics deals with the system in a general way. It only is concerned with the energy transfer without requiring specific information about the processes inside the boundaries. For this project the systems compared are the furnace alone and the furnace with a recuperator. The boundaries are drawn just inside the furnace walls and the load so as to include the energy flows to them within the energy balance. This is shown in Figure 52.

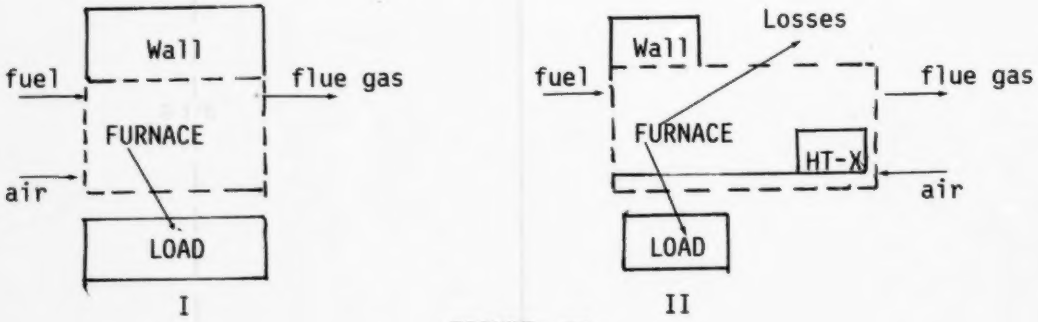

FIGURE 52

In each case the energy flows crossing the boundaries - cold fuel and air, hot flue gases, wall losses, and load - are the same. The only difference is that the flue gas exit temperature will be lower in the second case.

For an open flow, constant pressure system, the first law of thermodynamics is given by the following expression:

$$dQ - dW = dH + d(KE) \qquad (1)$$

where $Q$ = heat transfer

$W$ = work term

$H$ = enthalpy

$KE$ = kinetic energy

For the system under examination, there is no shaft work and changes of kinetic energy can be assumed small. In terms of the flows shown in Figure D-1:

$$\dot{Q}_P + \dot{Q}_L = \dot{M}_{FG}H_{FG} - (\dot{M}_A H_A + \dot{M}_F H_F) \tag{2}$$

where P = product

L = losses

FG = flue gas

A = air

F = fuel

The two system studies (one with, one without a recuperator) are compared by holding constant the enthalpy of the load, the losses, and the flue gas in both systems. Therefore, equation 2 can be manipulated so as to show the amount of fuel savings obtainable from preheating the combustion air. This derivation is done in detail in Appendix B.

Another way to compare the old system with the new system, which includes the recuperator, is to use the concept of efficiency which is the useful output divided by the input, or:

$$\eta = \frac{\text{useful output}}{\text{input}} \tag{3}$$

From equation 1 it can be said that the output and input are given by:

$$\text{useful output} = \dot{Q}_P + \dot{Q}_L \tag{4}$$

$$\text{input} = \dot{M}_A H_A + \dot{M}_F H_F \tag{5}$$

Combining these expressions and noting that the heat transferred equals the enthalpy flows across the boundaries, efficiency is given by:

$$\eta = 1 - \frac{\dot{M}_{FG}H_{FG}}{\dot{M}_A H_A + \dot{M}_F H_F} \tag{6}$$

Conservation of mass can be used to simplify this equation. For a combustion process:

$$\dot{M}_{FG} = \dot{M}_A + \dot{M}_F \tag{7}$$

$$\dot{M}_A = AF(1+E)\,\dot{M}_F \tag{8}$$

where AF = air/fuel ratio

E = percent excess air

Including this in equation 6 yields:

$$\eta = 1 - \frac{(1 + AF(1+E))H_{FG}}{H_F + AF(1+E)H_A} \tag{9}$$

The function the recuperator performs is to transfer heat from the outgoing flue gas to the incoming combustion air. The temperature of the flue gas decreases as it gives up its energy. From equation 9 it is seen that the efficiency is a function of the flue gas temperature. As the flue gas temperature decreases, efficiency increases. In fact, as $T_{FG} \to 0$, $\eta \to 1$. This is shown in Figure 53.

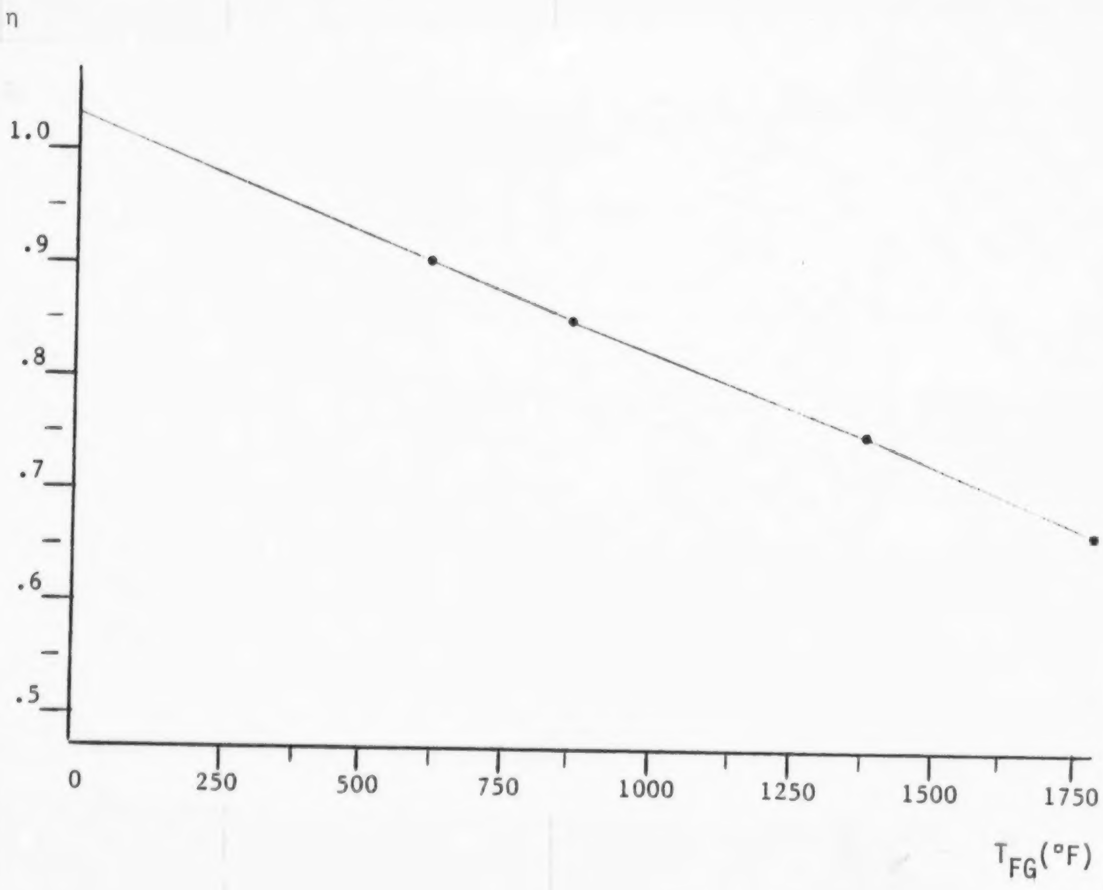

Figure 53. Efficiency versus flue gas temperature.

# APPENDIX E

## AVAILABILITY - SECOND LAW ANALYSIS

The advantage of using a first law thermodynamic analysis to demonstrate the merits of the furnace-recuperator system to a furnace alone was shown in Appendices B and D. Its value is to demonstrate the reduced fuel input required as a function of increasing combustion air preheat temperatures. Also, as the flue gas temperature decreases, a function of its transferring energy to the combustion air, the overall efficiency of the furnace system increases.

The purpose of including a second law analysis in the study is to measure the maximum amount of work in an energy stream and to identify the major sources of available energy decrease. A second law analysis demonstrates that the effect of adding preheated air to the step of the process--the combustion step in which the greatest irreversibilities are found --decreases the losses. As a result, the efficiency of the system increases and the amount of fuel required decreases.

What is desired, then, is an indicator of the maximum available work in the energy stream described by the term "availability." In the literature other measures of available energy exist (exergy, free energy, and essergy* ), and there is an ongoing discussion of their relative merits. Availability, as shown in Equation 1, is a generally accepted measure of the second law of thermodynamics and will be the parameter used consistently in this treatment of the subject.

There is energy present in the fuel/air reactants and the flue gas at the elevated temperatures. The question to be answered, though, is how much of that energy is available to do work: simply stated, availability is the maximum work that can be derived from an energy stream when it moves from an initial state to a final state. The issue of maximum work available is that there are thermodynamic irreversibilities associated with any state change--the combusting of the fuel/air into products of combustion--or with having gradients of properties, the fuel gas being at an elevated temperature relative to the environment.

The major source of irreversibilities in the system of study is in the combustion process where the fuel/air reactants are turned into products of combustion. A second law analysis of this step will clarify, from an energy standpoint, the source of the improvement of performance of the system.

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* Evans, R.G., "A Proof that Essergy is the Only Consistent Measure of Potential Work for Work Systems," Dartmouth College, Ph.D., 1969.

Availability is defined by the following expression:

$$\phi \equiv (\Delta H_{1-a} - T_a \ \Delta S_{1-a} + \ \Delta(PE) + \Delta(KE)) \qquad (1)$$

where H = enthalpy

T = temperature

S = entropy

PE = potential energy

KE = kinetic energy

1 = initial state of system

a = ambient environment

When kinetic and potential effects are insignificant, as they usually are in a chemical process, equation 1 becomes:

$$\phi \equiv \ - (\Delta H_{1-a} - T_a \Delta S_{1-a}) \qquad (2)$$

If a material moves through a flow process from an initial state (1) to a final state (2), that is not the atmospheric rest state (a), then it experiences a change, $\Delta\phi$, in availability:

$$\Delta\phi_{1-2} = \Delta H_{2-1} - T_a \Delta S_{2-1} \qquad (3)$$

That the expressions for availability are general and that, in fact, availability, $\phi$, is a property of the system are evident. Hence, $\Delta\phi$ depends only on the initial and final states and is independent of the path (as are enthalpy, H, and entropy, S).

For computing $\phi$ and $\Delta\phi$ of chemical reaction processes, the rest state of the products of combustion is defined at their normal state at $25^o$ and one atmosphere pressure, which is the same used for the tables on enthalpy of combustion. With the rest state so defined, the availability of any pure material at 25°C and one atmosphere pressure often is the negative of its free energy of formation minus the standard free energies of formation of its combustion products, which is designated by the symbol, $\phi_0$, and shown in the following expression:

$$\phi_o \text{ (of } C_xH_yO_z) = \ G^o(C_xH_yO_z) \ - \left[(xG^\circ(CO_2 \text{gas})\right]\left[\frac{Y}{2} \ G^\circ(H_2O \text{ liq})\right] \qquad (4)$$

Where $G^o$ is the standard free energy of formation, taken to be zero for an element.

When the pure material is at a temperature or pressure other than its standard state or is in a mixture, as would be fuel and air before combustion, then its availability changes from the standard state, the change being given by:

$$\phi_1 = \phi_0 + \Delta\phi_{0-1} \tag{5}$$

For a combustion system of pure methane (used because its physical and chemical properties are well-known and they are sufficiently close to those of natural gas), the combustion equation for stoichiometric combustion is:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 \tag{6}$$

The availabilities of the inlet stream and outlet stream are calculated by summing the availabilities of the individual constituents. The difference between the availabilities of the two streams is a measure of the thermodynamic irreversibilities, and, hence, a measure of the inefficiency of the waste heat recovery unit.

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# APPENDIX F

## REFERENCES ON FUEL $NO_x$ FORMATION

Information concerning the estimation of fuel $NO_x$ formation, while not discussed in this report, can be found in the following references.

1. Fenimore, C.P., "Formation of Nitric Oxide from Fuel Nitrogen in Ethylene Flames," *Combustion and Flame*, Vol. 19, pp. 289-296, 1972.

2. Turner, D.W., R.L. Andrews, and C.W. Siegmund, "Influence of Combustion Modification and Fuel Nitrogen Content on Nitrogen Oxides Emissions from Fuel Oil Combustion," *Air Pollution and Its Control*, American Institute of Chemical Engineers Symposium Series, 68:126, 1972.

3. Pershing, D.W. and J.O.L. Wendt, *Pulverized Coal Combustion: The Influence of Flame Temperature and Coal Composition on Thermal and Fuel* $NO_x$, presented at Sixteenth International Symposium on Combustion, Cambridge, Massachusetts, August 15-21, 1976.

4. Sarofim, A.F., J.H. Pohl, and B.R. Taylor, *Mechanisms and Kinetics of* $NO_x$ *Formation: Recent Developments*, presented at the 69th Annual Meeting, American Institute of Chemical Engineers, November 30, 1976.

5. Dykema, O.W., *Engineering Modeling of* $NO_x$ *Formation in Utility Boilers*, presented at the Winter Annual Meeting of the American Society of Mechanical Engineers, San Francisco, December 10-15, 1978.

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# APPENDIX G

## DIVISION OF STACK GAS WASTE HEAT INVENTORY IN VOLUMES 2 TO 10 OF REPORT

The waste heat inventories for different industrial processes are presented in tabular and histogram form by Source Classification Code (SCC) in Volumes 2 to 10 of the final report according to the following schedule:

| Volume Number | SCC's Covered |
|---|---|
| 2 | 1-01-001-01 to 1-02-007-03 |
| 3 | 1-02-007-04 to 2-03-999-98 |
| 4 | 2-04-001-01 to 3-01-025-05 |
| 5 | 3-01-025-10 to 3-02-013-01 |
| 6 | 3-02-014-01 to 3-04-002-03 |
| 7 | 3-04-002-04 to 3-05-010-03 |
| 8 | 3-05-010-99 to 3-06-010-01 |
| 9 | 3-06-011-01 to 3-90-005-33 |
| 10 | 3-90-005-99 to 3-90-008-99 |

The industrial process associated with each SCC is provided in abbreviated form at the top of each table or histogram and is described more completely in Appendix H of Volume 1.

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# APPENDIX H

## TITLE MANUAL FOR SOURCE CODE CLASSIFICATIONS

To develop a stack gas waste heat inventory this study analyzed the stack gas data for numerous industrial processes as compiled in EPA's National Emissions Data System (NEDS). NEDS is a collection of emissions data obtained from individual industrial processes located throughout the United States. These data are categorized in NEDS by Source Classification Code (SCC). What follows is a title manual which associates each type of industrial process with a SCC number.

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## EXTERNAL COMBUSTION BOILERS

### ELECTRIC GENERATION

| Anthracite Coal | | SCC Units |
|---|---|---|
| 1-01-001-01 | >100 MMBTU/HR Pulverized | tons burned |
| 1-01-001-02 | >100 MMBTU/HR Stoker | tons burned |
| 1-01-001-03 | 10-100 MMBTU/HR Pulverized | tons burned |
| 1-01-001-04 | 10-100 MMBTU/HR Stoker | tons burned |
| 1-01-001-05 | <10 MMBTU/HR Pulverized | tons burned |
| 1-01-001-06 | <10 MMBTU/HR Stoker | tons burned |
| 1-01-001-99 | other/not classified | tons burned |

Bituminous Coal

| | | |
|---|---|---|
| 1-01-002-01 | >100 MMBTU/HR Pulverized Wet | tons burned |
| 1-01-002-02 | >100 MMBTU/HR Pulverized Dry | tons burned |
| 1-01-002-03 | >100 MMBTU/HR Cyclone | tons burned |
| 1-01-002-04 | >100 MMBTU/HR Spreader Stoker | tons burned |
| 1-01-002-05 | >100 MMBTU/HR Over Fired Stoker | tons burned |
| 1-01-002-06 | 10-100 MMBTU/HR Pulverized Wet | tons burned |
| 1-01-002-07 | 10-100 MMBTU/HR Pulverized Dry | tons burned |
| 1-01-002-08 | 10-100 MMBTU/HR Over Fired Stoker | tons burned |
| 1-01-002-09 | 10-100 MMBTU/HR Under Fired Stoker | tons burned |
| 1-01-002-10 | <10 MMBTU/HR Over Fired Stoker | tons burned |
| 1-01-002-11 | <10 MMBTU/HR Under Fired Stoker | tons burned |
| 1-01-002-12 | <10 MMBTU/HR Pulverized Dry | tons burned |
| 1-01-002-99 | other/not classified | tons burned |

Lignite

| | | |
|---|---|---|
| 1-01-003-01 | >100 MMBTU/HR Pulverized Wet | tons burned |
| 1-01-003-02 | >100 MMBTU/HR Pulverized Dry | tons burned |
| 1-01-003-03 | >100 MMBTU/HR Cyclone | tons burned |
| 1-01-003-04 | >100 MMBTU/HR Over Fired Stoker | tons burned |
| 1-01-003-05 | >100 MMBTU/HR Under Fired Stoker | tons burned |
| 1-01-003-06 | >100 MMBTU/HR Spreader Stoker | tons burned |
| 1-01-003-07 | 10-100 MMBTU/HR Dry Pulverized | tons burned |
| 1-01-003-08 | 10-100 MMBTU/HR Wet Pulverized | tons burned |
| 1-01-003-09 | 10-100 MMBTU/HR Over Fired Stoker | tons burned |
| 1-01-003-10 | 10-100 MMBTU/HR Under Fired Stoker | tons burned |
| 1-01-003-11 | 10-100 MMBTU/HR Spreader Stoker | tons burned |
| 1-01-003-12 | <10 MMBTU/HR Pulverized Dry | tons burned |
| 1-01-003-13 | <10 MMBTU/HR Over Fired Stoker | tons burned |
| 1-01-003-14 | <10 MMBTU/HR Under Fired Stoker | tons burned |
| 1-01-003-15 | <10 MMBTU/HR Spreader Stoker | tons burned |

Subject: Source Classification
Codes (SCC)

## EXTERNAL COMBUSTION BOILERS - ELECTRIC GENERATION

| | | SCC Units |
|---|---|---|
| **Residual Oil** | | |
| 1-01-004-01 | >100 MMBTU/HR General | 1000 gallons burned |
| 1-01-004-02 | 10-100 MMBTU/HR General | 1000 gallons burned |
| 1-01-004-03 | <10 MMBTU/HR General | 1000 gallons burned |
| **Distillate Oil** | | |
| 1-01-005-01 | >100 MMBTU/HR General | 1000 gallons burned |
| 1-01-005-02 | 10-100 MMBTU/HR General | 1000 gallons burned |
| 1-01-005-03 | <10 MMBTU/HR General | 1000 gallons burned |
| **Natural Gas** | | |
| 1-01-006-01 | >100 MMBTU/HR | million cubic feet burned |
| 1-01-006-02 | 10-100 MMBTU/HR | million cubic feet burned |
| 1-01-006-03 | <10 MMBTU/HR | million cubic feet burned |
| **Process Gas** | | |
| 1-01-007-01 | >100 MMBTU/HR | million cubic feet burned |
| 1-01-007-02 | 10-100 MMBTU/HR | million cubic feet burned |
| 1-01-007-03 | <10 MMBTU/HR | million cubic feet burned |
| **Coke** | | |
| 1-01-008-01 | >100 MMBTU/HR | tons burned |
| **Wood/Bark Waste** | | |
| 1-01-009-01 | Bark Boiler | tons burned |
| 1-01-009-02 | Wood/Bark Boiler | tons burned |
| 1-01-009-03 | Wood Boiler | tons burned |
| **Bagasse** | | |
| 1-01-011-01 | >100 MMBTU/HR | tons burned |
| 1-01-011-02 | 10-100 MMBTU/HR | tons burned |
| 1-01-011-03 | <10 MMBTU/HR | tons burned |
| **Solid Waste - Specify** | | |
| 1-01-012-01 | >100 MMBTU/HR | tons burned |
| 1-01-012-02 | 10-100 MMBTU/HR | tons burned |
| 1-01-012-03 | <10 MMBTU/HR | tons burned |
| **Liquid Waste - Specify** | | |
| 1-01-013-01 | >100 MMBTU/HR | 1000 gallons burned |
| 1-01-013-02 | 10-100 MMBTU/HR | 1000 gallons burned |
| 1-01-013-03 | <10 MMBTU/HR | 1000 gallons burned |

## EXTERNAL COMBUSTION BOILERS - ELECTRIC GENERATION

| Other/Not Classified | | SCC Units |
|---|---|---|
| 1-01-999-97 | Specify in Remark | million cubic feet burn |
| 1-01-999-98 | Specify in Remark | 1000 gallons burned (liquid) |
| 1-01-999-99 | Specify in Remark | tons burned (solid) |

## EXTERNAL COMBUSTION BOILERS - INDUSTRIAL

| Anthracite Coal | | SCC Units |
|---|---|---|
| 1-02-001-01 | >100 MMBTU/HR Pulverized | tons burned |
| 1-02-001-02 | >100 MMBTU/HR Stoker | tons burned |
| 1-02-001-03 | 10-100 MMBTU/HR Pulverized | tons burned |
| 1-02-001-04 | 10-100 MMBTU/HR Stoker | tons burned |
| 1-02-001-05 | <10 MMBTU/HR Pulverized | tons burned |
| 1-02-001-06 | <10 MMBTU/HR Stoker | tons burned |
| 1-02-001-07 | <10 MMBTU/HR Handfire | tons burned |
| 1-02-001-99 | other/not classified | tons burned |
| **Bituminous Coal** | | |
| 1-02-002-01 | >100 MMBTU/HR Pulverized Wet | tons burned |
| 1-02-002-02 | >100 MMBTU/HR Pulverized Dry | tons burned |
| 1-02-002-03 | >100 MMBTU/HR Cyclone | tons burned |
| 1-02-002-04 | >100 MMBTU/HR Spreader Stoker | tons burned |
| 1-02-002-05 | 10-100 MMBTU/HR Over Fired Stoker | tons burned |
| 1-02-002-06 | 10-100 MMBTU/HR Under Fired Stoker | tons burned |
| 1-02-002-07 | 10-100 MMBTU/HR Pulverized Wet | tons burned |
| 1-02-002-08 | 10-100 MMBTU/HR Pulverized Dry | tons burned |
| 1-02-002-09 | 10-100 MMBTU/HR Spreader Stoker | tons burned |
| 1-02-002-10 | <10 MMBTU/HR Over Fired Stoker | tons burned |
| 1-02-002-11 | <10 MMBTU/HR Under Fired Stoker | tons burned |
| 1-02-002-12 | <10 MMBTU/HR Pulverized Dry | tons burned |
| 1-02-002-13 | <10 MMBTU/HR Spreader Stoker | tons burned |
| 1-02-002-14 | <10 MMBTU/HR Handfire | tons burned |
| 1-02-002-99 | other/not classified | tons burned |
| **Lignite** | | |
| 1-02-003-01 | >100 MMBTU/HR Pulverized Wet | tons burned |
| 1-02-003-02 | >100 MMBTU/HR Pulverized Dry | tons burned |
| 1-02-003-03 | >100 MMBTU/HR Cyclone | tons burned |
| 1-02-003-04 | >100 MMBTU/HR Over Fired Stoker | tons burned |
| 1-02-003-05 | >100 MMBTU/HR Under Fired Stoker | tons burned |
| 1-02-003-06 | >100 MMBTU/HR Spreader Stoker | tons burned |
| 1-02-003-07 | 10-100 MMBTU/HR Pulverized Dry | tons burned |
| 1-02-003-08 | 10-100 MMBTU/HR Pulverized Wet | tons burned |
| 1-02-003-09 | 10-100 MMBTU/HR Over Fired Stokers | tons burned |
| 1-02-003-10 | 10-100 MMBTU/HR Under Fired Stoker | tons burned |
| 1-02-003-11 | 10-100 MMBTU/HR Spreader Stoker | tons burned |
| 1-02-003-12 | <10 MMBTU/HR Pulverized Dry | tons burned |
| 1-02-003-13 | <10 MMBTU/HR Over Fired Stoker | tons burned |
| 1-02-003-14 | <10 MMBTU/HR Under Fired Stoker | tons burned |
| 1-02-003-15 | <10 MMBTU/HR Handfire | tons burned |
| 1-02-003-16 | <10 MMBTU/HR Spreader Stoker | tons burned |

Subject: Source Classificat
Codes (SCC)

## EXTERNAL COMBUSTION BOILERS - INDUSTRIAL

| | | SCC Units |
|---|---|---|
| **Residual Oil** | | |
| 1-02-004-01 | >100 MMBTU/HR | 1000 gallons burned |
| 1-02-004-02 | 10-100 MMBTU/HR | 1000 gallons burned |
| 1-02-004-03 | <10 MMBTU/HR | 1000 gallons burned |
| **Distillate Oil** | | |
| 1-02-005-01 | >100 MMBTU/HR | 1000 gallons burned |
| 1-02-005-02 | 10-100 MMBTU/HR | 1000 gallons burned |
| 1-02-005-03 | <10 MMBTU/HR | 1000 gallons burned |
| **Natural Gas** | | |
| 1-02-006-01 | >100 MMBTU/HR | million cubic feet burn |
| 1-02-006-02 | 10-100 MMBTU/HR | million cubic feet burn |
| 1-02-006-03 | <10 MMBTU/HR | million cubic feet burn |
| **Process Gas** | | |
| 1-02-007-01 | >100 MMBTU/HR Refinery | million cubic feet burne |
| 1-02-007-02 | 10-100 MMBTU/HR Refinery | million cubic feet burne |
| 1-02-007-03 | <10 MMBTU/HR Refinery | million cubic feet burne |
| 1-02-007-04 | >100 MMBTU/HR Blast Furnace | million cubic feet burne |
| 1-02-007-05 | 10-100 MMBTU/HR Blast Furnace | million cubic feet burne |
| 1-02-007-06 | <10 MMBTU/HR Blast Furnace | million cubic feet burne |
| 1-02-007-07 | >100 MMBTU/HR Coke Oven | million cubic feet burne |
| 1-02-007-08 | 10-100 MMBTU/HR Coke Oven | million cubic feet burne |
| 1-02-007-09 | <10 MMBTU/HR Coke Oven | million cubic feet burne |
| 1-02-007-99 | other/not classified | million cubic feet burne |
| **Coke** | | |
| 1-02-008-02 | 10-100 MMBTU/HR | tons burned |
| 1-02-008-03 | <10 MMBTU/HR | tons burned |
| **Wood/Bark Waste** | | |
| 1-02-009-01 | Bark Boiler | tons burned |
| 1-02-009-02 | Wood/Bark Boiler | tons burned |
| 1-02-009-03 | Wood Boiler | tons burned |
| **Liquid Petroleum Gas** | | |
| 1-02-010-02 | 10-100 MMBTU/HR | 1000 gallons burned |
| 1-02-010-03 | <100 MMBTU/HR | 1000 gallons burned |

## EXTERNAL COMBUSTION BOILERS - INDUSTRIAL

| | | SCC Units |
|---|---|---|
| Bagasse | | |
| 1-02-011-01 | >100 MMBTU/HR | tons burned |
| 1-02-011-02 | 10-100 MMBTU/HR | tons burned |
| 1-02-011-03 | <10 MMBTU/HR | tons burned |
| Solid Waste - Specify | | |
| 1-02-012-01 | >100 MMBTU/HR | tons burned |
| 1-02-012-02 | 10-100 MMBTU/HR | tons burned |
| 1-02-012-03 | <10 MMBTU/HR | tons burned |
| Liquid Waste - Specify | | |
| 1-02-013-01 | >100 MMBTU/HR | 1000 gallons burned |
| 1-02-013-02 | 10-100 MMBTU/HR | 1000 gallons burned |
| 1-02-013-03 | <10 MMBTU/HR | 1000 gallons burned |
| Other/Not Classified | | |
| 1-02-999-97 | Specify in Remark | million cubic feet burned |
| 1-02-999-98 | Specify in Remark | 1000 gallons burned (liquid) |
| 1-02-999-99 | Specify in Remark | tons burned (solid) |

## EXTERNAL COMBUSTION BOILERS - COMMERCIAL INSTITUTIONAL

### Anthracite Coal

| | | SCC Units |
|---|---|---|
| 1-03-001-05 | 10-100 MMBTU/HR Pulverized Wet | tons burned |
| 1-03-001-06 | 10-100 MMBTU/HR Pulverized Dry | tons burned |
| 1-03-001-07 | 10-100 MMBTU/HR Spreader Stoker | tons burned |
| 1-03-001-08 | <10 MMBTU/HR Pulverized | tons burned |
| 1-03-001-09 | <10 MMBTU/HR Stoker | tons burned |
| 1-03-001-10 | <10 MMBTU/HR Spreader Stoker | tons burned |
| 1-03-001-99 | other/not classified | tons burned |

### Bituminous Coal

| | | |
|---|---|---|
| 1-03-002-05 | 10-100 MMBTU/HR Pulverized Wet | tons burned |
| 1-03-002-06 | 10-100 MMBTU/HR Pulverized Dry | tons burned |
| 1-03-002-07 | 10-100 MMBTU/HR Over Fired Stoker | tons burned |
| 1-03-002-08 | 10-100 MMBTU/HR Under Fired Stoker | tons burned |
| 1-03-002-09 | 10-100 MMBTU/HR Spreader Stoker | tons burned |
| 1-03-002-10 | 10-100 MMBTU/HR Handfire | tons burned |
| 1-03-002-11 | <10 MMBTU/HR Over Fired Stoker | tons burned |
| 1-03-002-12 | <10 MMBTU/HR Under Fired Stoker | tons burned |
| 1-03-002-13 | <10 MMBTU/HR Spreader Stoker | tons burned |
| 1-03-002-14 | <10 MMBTU/HR Handfire | tons burned |
| 1-03-002-99 | other/not classified | tons burned |

### Lignite

| | | |
|---|---|---|
| 1-03-003-05 | 10-100 MMBTU/HR Pulverized Wet | tons burned |
| 1-03-003-06 | 10-100 MMBTU/HR Pulverized Dry | tons burned |
| 1-03-003-07 | 10-100 MMBTU/HR Over Fired Stoker | tons burned |
| 1-03-003-08 | 10-100 MMBTU/HR Under Fired Stoker | tons burned |
| 1-03-003-09 | 10-100 MMBTU/HR Spreader Stoker | tons burned |
| 1-03-003-10 | <10 MMBTU/HR Pulverized Dry | tons burned |
| 1-03-003-11 | <10 MMBTU/HR Over Fired Stoker | tons burned |
| 1-03-003-12 | <10 MMBTU/HR Under Fired Stoker | tons burned |
| 1-03-003-13 | <10 MMBTU/HR Spreader Stoker | tons burned |
| 1-03-003-14 | <10 MMBTU/HR Handfire | tons burned |

### Residual Oil

| | | |
|---|---|---|
| 1-03-004-01 | >100 MMBTU/HR | 1000 gallons burned |
| 1-03-004-02 | 10-100 MMBTU/HR | 1000 gallons burned |
| 1-03-004-03 | <10 MMBTU/HR | 1000 gallons burned |

### Distillate

| | | |
|---|---|---|
| 1-03-005-01 | >100 MMBTU/HR | 1000 gallons burned |
| 1-03-005-02 | 10-100 MMBTU/HR | 1000 gallons burned |
| 1-03-005-03 | <10 MMBTU/HR | 1000 gallons burned |

## EXTERNAL COMBUSTION BOILERS - COMMERCIAL INSTITUTIONAL

| | | SCC Units |
|---|---|---|
| Natural Gas | | |
| 1-03-006-01 | <100 MMBTU/HR | million cubic feet burned |
| 1-03-006-02 | 10-100 MMBTU/HR | million cubic feet burned |
| 1-03-006-03 | <10 MMBTU/HR | million cubic feet burned |
| Process Gas | | |
| 1-03-007-01 | <100 MMBTU/HR Sewage | million cubic feet burned |
| 1-03-007-02 | 10-100 MMBTU/HR Sewage | million cubic feet burned |
| 1-03-007-03 | <10 MMBTU/HR Sewage | million cubic feet burned |
| 1-03-007-99 | other/not classified | million cubic feet burned |
| Wood/Bark Waste | | |
| 1-03-009-01 | Bark Boiler | tons burned |
| 1-03-009-02 | Wood/Bark Boiler | tons burned |
| 1-03-009-03 | Wood Boiler | tons burned |
| Liquid Petroleum Gas | | |
| 1-03-010-02 | 10-100 MMBTU/HR | 1000 gallons burned |
| 1-03-010-03 | <10 MMBTU/HR | 1000 gallons burned |
| Solid Waste - Specify | | |
| 1-03-012-01 | <100 MMBTU/HR | tons burned |
| 1-03-012-02 | 10-100 MMBTU/HR | tons burned |
| 1-03-012-03 | <10 MMBTU/HR | tons burned |
| Liquid Waste - Specify | | |
| 1-03-013-01 | <100 MMBTU/HR | 1000 gallons burned |
| 1-03-013-02 | 10-100 MMBTU/HR | 1000 gallons burned |
| 1-03-013-03 | <10 MMBTU/HR | 1000 gallons burned |
| Other/Not Classified | | |
| 1-03-999-97 | Specify in Remark | million cubic feet burned |
| 1-03-999-98 | Specify in Remark | 1000 gallons burned (liquid) |
| 1-03-999-99 | Specify in Remark | tons burned (solid) |

## EXTERNAL COMBUSTION BOILERS - SPACE HEATER

| Industrial | | SCC Units |
|---|---|---|
| 1-05-001-01 | Anthracite Coal | tons burned |
| 1-05-001-02 | Bituminous Coal | tons burned |
| 1-05-001-03 | Lignite | tons burned |
| 1-05-001-04 | Residual Oil | 1000 gallons burned |
| 1-05-001-05 | Distillate Oil | 1000 gallons burned |
| 1-05-001-06 | Natural Gas | million cubic feet burned |
| 1-05-001-10 | Liquid Petroleum Gas | 1000 gallons burned |
| 1-05-001-97 | Other - Specify | tons burned |
| 1-05-001-98 | Other - Specify | 1000 gallons burned |
| 1-05-001-99 | Other - Specify | million cubic feet burned |

| Commercial Institutional | | SCC Units |
|---|---|---|
| 1-05-002-01 | Anthracite Coal | tons burned |
| 1-05-002-02 | Bituminous Coal | tons burned |
| 1-05-002-03 | Lignite | tons burned |
| 1-05-002-04 | Residual Oil | 1000 gallons burned |
| 1-05-002-05 | Distillate Oil | 1000 gallons burned |
| 1-05-002-06 | Natural Gas | million cubic feet burned |
| 1-05-002-10 | Liquid Petroleum Gas | 1000 gallons burned |
| 1-05-002-97 | Other - Specify | tons burned |
| 1-05-002-98 | Other - Specify | 1000 gallons burned |
| 1-05-002-99 | Other - Specify | million cubic feet burned |

## INTERNAL COMBUSTION BOILERS

### ELECTRIC GENERATION

| | | SCC Units |
|---|---|---|
| Distillate Oil | | |
| 2-01-001-01 | Turbine | 1000 gallons burned |
| 2-01-001-02 | Reciprocating | 1000 gallons burned |
| Natural Gas | | |
| 2-01-002-01 | Turbine | million cubic feet |
| 2-01-002-02 | Reciprocating | million cubic feet |
| Diesel | | |
| 2-01-003-01 | Reciprocating | thousands of gallons |
| 2-01-003-02 | Turbine | 1000 gallons burned |
| Residual Oil | | |
| 2-01-004-01 | Turbine | 1000 gallons burned |
| Jet Fuel | | |
| 2-01-005-01 | Turbine | 1000 gallons burned |
| Crude Oil | | |
| 2-01-006-01 | Turbine | 1000 gallons burned |
| Process Gas | | |
| 2-01-007-01 | Turbine | million cubic feet |
| Other/Not Classified | | |
| 2-01-999-97 | Specify in Remark | million cubic feet burned |
| 2-01-999-98 | Specify in Remark | 1000 gallons burned |

## INTERNAL COMBUSTION BOILERS - INDUSTRIAL

| | | SCC Units |
|---|---|---|
| Distillate Oil | | |
| 2-02-001-01 | Turbine | 1000 gallons burned |
| 2-02-001-02 | Reciprocating | 1000 gallons burned |
| Natural Gas | | |
| 2-02-002-01 | Turbine | million cubic feet |
| 2-02-002-02 | Reciprocating | million cubic feet |
| Gasoline | | |
| 2-02-003-01 | Reciprocating | 1000 gallons burned |
| Diesel Fuel | | |
| 2-02-004-01 | Reciprocating | 1000 gallons burned |
| 2-02-004-02 | Turbine | 1000 gallons burned |
| Residual Oil | | |
| 2-02-005-01 | Turbine | 1000 gallons burned |
| Jet Fuel | | |
| 2-02-006-01 | Turbine | 1000 gallons burned |
| Crude Oil | | |
| 2-02-007-01 | Turbine | 1000 gallons burned |
| Process Gas | | |
| 2-02-008-01 | Turbine | million cubic feet |
| 2-02-008-02 | Reciprocating | million cubic feet burned |
| Other/Not Classified | | |
| 2-02-999-97 | Specify in Remark | million cubic feet burned |
| 2-02-999-98 | Specify in Remark | 1000 gallons burned |

## INTERNAL COMBUSTION BOILERS - COMMERCIAL INSTITUTIONAL

| | | SCC Units |
|---|---|---|
| Diesel | | |
| 2-03-001-01 | Reciprocating | thousands of gallons |
| Other/Not Classified | | |
| 2-03-999-97 | Specify in Remark | millions cubic feet burned |
| 2-03-999-98 | Specify in Remark | 1000 gallons burned |

## INTERNAL COMBUSTION BOILERS - ENGINE TESTING

| | | SCC Units |
|---|---|---|
| **Aircraft** | | |
| 2-04-001-01 | Turbojet | thousands of gallon/fuel |
| **Rocket Motor** | | |
| 2-04-002-01 | Solid Propellant | tons of fuel |
| **Other/Not Classified** | | |
| 2-04-999-97 | Specify in Remark | million cubic feet burned |
| 2-04-999-98 | Specify in Remark | 1000 gallons burned |
| 2-04-999-99 | Specify in Remark | tons burned |

## INDUSTRIAL PROCESS

### CHEMICAL MANUFACTURING

**Adipic Acid Product**

| | | SCC Units |
|---|---|---|
| 3-01-001-01 | General Cyclohex | tons produced |
| 3-01-001-99 | Other/Not Classified | tons produced |

**Ammonia with Methonator**

| | | |
|---|---|---|
| 3-01-002-01 | Purge Gas | tons produced |
| 3-01-002-02 | Storage/Loading | tons produced |

**Ammonia with CO Absorber**

| | | |
|---|---|---|
| 3-01-003-01 | Regenerator Exit | tons produced |
| 3-01-003-02 | Purge Gas | tons produced |
| 3-01-003-03 | Storage/Loading | tons produced |
| 3-01-003-99 | Other/Not Classified | tons produced |

**Ammonium Nitrate**

| | | |
|---|---|---|
| 3-01-004-01 | General | tons produced |
| 3-01-004-99 | Other/Not Classified | tons produced |

**Carbon Black**

| | | |
|---|---|---|
| 3-01-005-01 | Channel Process | tons produced |
| 3-01-005-02 | Thermal Process | tons produced |
| 3-01-005-03 | Furnace Process Gas | tons produced |
| 3-01-005-04 | Furnace Process Oil | tons produced |
| 3-01-005-05 | Furnace with Gas/Oil | tons produced |
| 3-01-005-99 | Other/Not Classified | tons produced |

**Charcoal Manufacturing**

| | | |
|---|---|---|
| 3-01-006-01 | Pyrolysis/Distillation/General | tons produced |
| 3-01-006-99 | Other/Not Classified | tons produced |

**Chlorine**

| | | |
|---|---|---|
| 3-01-007-01 | General | tons produced |
| 3-01-007-99 | Other/Not Classified | tons produced |

**Chlor-Alkali**

| | | |
|---|---|---|
| 3-01-008-01 | Liquification-Diaphragm | 100 tons chlorine liquified |
| 3-01-008-02 | Liquification-Mercury Cell | 100 tons chlorine liquified |
| 3-01-008-03 | Loading Tank Car Vent | 100 tons chlorine liquified |
| 3-01-008-04 | Loading Storage Tank Vent | 100 tons chlorine liquified |
| 3-01-008-05 | Air-Blow Mercury Cell Brine | 100 tons chlorine liquified |
| 3-01-008-99 | Other/Not Classified | 100 tons chlorine liquified |

Subject: Source Classification
Codes (SCC)

## INDUSTRIAL PROCESS - CHEMICAL MANUFACTURING

| | | SCC Units |
|---|---|---|
| **Cleaning Chemicals** | | |
| 3-01-009-01 | Soap/Detergent Spray Dryer | tons produced |
| 3-01-009-10 | Specialty Cleaners | tons produced |
| 3-01-009-99 | Other/Not Classified | tons produced |
| **Explosives-TNT** | | |
| 3-01-010-01 | Nitration Reactors | tons produced |
| 3-01-010-02 | HNO3 Concentrators | tons produced |
| 3-01-010-03 | H2SO4 Regenerator | tons produced |
| 3-01-010-04 | Red Water Incinerator | tons produced |
| 3-01-010-05 | Open Waste Burn | tons burned |
| 3-01-010-06 | Sellite Exhaust | tons produced |
| 3-01-010-99 | Other/Not Classifed | tons produced |
| **Hydrochloric Acid** | | |
| 3-01-011-01 | Byproduct without Scrubber | tons final acid |
| 3-01-011-02 | Byproduct with Scrubber | tons final acid |
| 3-01-011-99 | Other/Not Classified | tons final acid |
| **Hydrofluoric Acid** | | |
| 3-01-012-01 | Rotary Kiln with Scrubber | tons acid |
| 3-01-012-02 | Rotary Kiln without Scrubber | tons acid |
| 3-01-012-03 | Grind/Dry Fluorspar | tons fluorine |
| 3-01-012-99 | Other/Not Classified | tons acid |
| **Nitric Acid** | | |
| 3-01-013-01 | Ammonia Oxidation Old | tons pure acid produced |
| 3-01-013-02 | Ammonia Oxidation New | tons pure acid produced |
| 3-01-013-03 | Nitric Acid Concentrator Old | tons pure acid produced |
| 3-01-013-04 | Nitric Acid Concentrator New | tons pure acid produced |
| 3-01-013-05 | Uncontrolled | tons pure acid produced |
| 3-01-013-06 | With Catalytic Combuster | tons pure acid produced |
| 3-01-013-07 | Uncontrolled | tons pure acid produced |
| 3-01-013-08 | With Absorbers | tons pure acid produced |
| 3-01-013-99 | Other/Not Classified | tons pure acid produced |
| **Paint Manufacturing** | | |
| 3-01-014-01 | General | tons produced |
| 3-01-014-02 | Pigment Kiln | tons produced |
| 3-01-014-99 | Other/Not Classified | tons produced |
| **Varnish Manufacturing** | | |
| 3-01-015-01 | Bodying Oil General | tons produced |
| 3-01-015-02 | Oleo Resinous General | tons produced |
| 3-01-015-03 | Alkyd General | tons produced |

## INDUSTRIAL PROCESS - CHEMICAL MANUFACTURING

| | | SCC Units |
|---|---|---|
| Phos-Acid Wet Process | | |
| 3-01-016-01 | Reactor Uncontrolled | tons phosphate rock |
| 3-01-016-02 | Gypsum Pond | tons phosphate rock |
| 3-01-016-03 | Condenser Uncontrolled | tons phosphate rock |
| 3-01-016-99 | Other/Not Classified | tons produced |
| Phos-Acid Thermal | | |
| 3-01-017-01 | General | tons phosphorous burned |
| 3-01-017-99 | Other/Not Classified | tons produced |
| Plastics | | |
| 3-01-018-01 | PVC-General | tons produced |
| 3-01-018-02 | Polypropylene-General | tons produced |
| 3-01-018-05 | Bakelite-General | tons produced |
| 3-01-018-99 | Other/Not Classified | tons produced |
| Phthalic Anhydrid | | |
| 3-01-019-03 | Uncontrolled-General | tons produced |
| Printing Ink | | |
| 3-01-020-01 | Cooking-General | tons produced |
| 3-01-020-02 | Cooking-Oils | tons produced |
| 3-01-020-03 | Cooking-Oleo Resin | tons produced |
| 3-01-020-04 | Cooking-Alkyds | tons produced |
| 3-01-020-05 | Pigment Mixing General | tons pigment |
| 3-01-020-99 | Other/Not Classified | tons produced |
| Sodium Carbonate | | |
| 3-01-021-01 | Solvay-NH3 Recovery | tons produced |
| 3-01-021-02 | Solvay-Handling | tons produced |
| 3-01-021-10 | Trona-Calcining | tons produced |
| 3-01-021-11 | Trona-Dryer | tons produced |
| 3-01-021-20 | Brine Evaporation-General | tons produced |
| 3-01-021-99 | Other/Not Classified | tons produced |
| H2SO4 Chamber | | |
| 3-01-022-01 | General | tons pure acid produced |
| H2SO4 Contact | | |
| 3-01-023-01 | 99.7 Conversion | tons pure acid produced |
| 3-01-023-04 | 99.5 Conversion | tons pure acid produced |
| 3-01-023-06 | 99.0 Conversion | tons pure acid produced |
| 3-01-023-08 | 98.0 Conversion | tons pure acid produced |

## INDUSTRIAL PROCESS - CHEMICAL MANUFACTURING

H2S04 Contact (continued)

| | | SCC Units |
|---|---|---|
| 3-01-023-10 | 97.0 Conversion | tons pure acid produced |
| 3-01-023-12 | 96.0 Conversion | tons pure acid produced |
| 3-01-023-14 | 95.0 Conversion | tons pure acid produced |
| 3-01-023-16 | 94.0 Conversion | tons pure acid produced |
| 3-01-023-18 | 93.0 Conversion | tons pure acid produced |
| 3-01-023-99 | Other/Not Classified | tons produced |

Synthetic Fibers

| | | |
|---|---|---|
| 3-01-024-01 | Nylon General | tons fiber |
| 3-01-024-02 | Dacron General | tons fiber |
| 3-01-024-03 | Orlon | tons produced |
| 3-01-024-04 | Elastic | tons produced |
| 3-01-024-05 | Teflon | tons produced |
| 3-01-024-06 | Polyester | tons produced |
| 3-01-024-08 | Nomex | tons produced |
| 3-01-024-10 | Acrylic | tons produced |
| 3-01-024-12 | Tyvex | tons produced |
| 3-01-024-14 | Olefins | tons produced |
| 3-01-024-99 | Others/Not Classified | tons produced |

Semisynthetic Fibers

| | | |
|---|---|---|
| 3-01-025-01 | Rayon General | tons fiber |
| 3-01-025-05 | Acetate | tons produced |
| 3-01-025-10 | Viscose | tons produced |
| 3-01-025-99 | Others/Not Classified | tons produced |

Synthetic Rubber

| | | |
|---|---|---|
| 3-01-026-01 | Butadiene General | tons produced |
| 3-01-026-02 | Methylpropene General | tons produced |
| 3-01-026-03 | Butyne General | tons produced |
| 3-01-026-04 | Pentadiene General | tons produced |
| 3-01-026-05 | Dimethmeptne General | tons produced |
| 3-01-026-06 | Pentane General | tons produced |
| 3-01-026-07 | Ethanenitrile General | tons produced |
| 3-01-026-08 | Acrylonitrile General | tons produced |
| 3-01-026-09 | Acrolein General | tons produced |
| 3-01-026-20 | Auto Tires General | tons produced |
| 3-01-026-99 | Other/Not Classified | tons produced |

Fertilizer Ammonium Nitrate

| | | |
|---|---|---|
| 3-01-027-01 | Prilling Water-Neutralizer | tons produced |
| 3-01-027-02 | Prilling Tower | tons produced |
| 3-01-027-03 | Prilling Water- Dry Coolers | tons produced |
| 3-01-027-04 | Granulator-Neutralizer | tons produced |
| 3-01-027-05 | Granulator | tons produced |
| 3-01-027-06 | Granulator-Dry Coolers | tons produced |

## INDUSTRIAL PROCESS - CHEMICAL MANUFACTURING

| | | SCC Units |
|---|---|---|
| Fertilizer Normal Super Phosphate | | |
| 3-01-028-01 | Grinder Dryer | tons produced |
| 3-01-028-02 | Main Stack | tons produced |
| Fertilizer Triple Super Phosphate | | |
| 3-01-029-01 | Run-of-Pile | tons produced |
| 3-01-029-02 | Granular | tons produced |
| Fertilizer Diammonium Phosphate | | |
| 3-01-030-01 | Dryer-Coolers | tons produced |
| 3-01-030-02 | Ammoniator-Granulator | tons produced |
| 3-01-030-99 | Other/Not Classified | tons produced |
| Terepthalic Acid | | |
| 3-01-031-01 | HNO3 Paraxylene Generator | tons produced |
| 3-01-031-99 | Other/Not Classified | tons produced |
| Sulfur (Elemental) | | |
| 3-01-032-01 | Modified-Claus Process 2 Stage | tons produced |
| 3-01-032-02 | Modified-Claus Process 3 Stage | tons produced |
| 3-01-032-03 | Modified-Claus Process 4 Stage | tons produced |
| 3-01-032-99 | Other/Not Classified | tons produced |
| Pesticides | | |
| 3-01-033-01 | Malathion | gallons of product |
| 3-01-033-99 | Other/Not Classified | tons produced |
| Amines/Amides | | |
| 3-01-034-01 | General/Other | tons produced |
| Pigment-Inorganic | | |
| 3-01-035-01 | Calcination | tons produced |
| 3-01-035-99 | Other/Not Classified | tons produced |
| Sodium Sulfate | | |
| 3-01-036-01 | General/Other | tons produced |
| 3-01-036-02 | Kilns | tons produced |
| Sodium Sulfite | | |
| 3-01-037-01 | General/Other | tons produced |
| 3-01-037-02 | Kilns | tons produced |

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## INDUSTRIAL PROCESS - CHEMICAL MANUFACTURING

| | | SCC Units |
|---|---|---|
| Sodium Bicarbonate | | |
| 3-01-038-01 | General | tons produced |
| Lithium Hydroxide | | |
| 3-01-039-01 | General | tons produced |
| Fertilizer Urea | | |
| 3-01-040-01 | General | tons produced |
| Nitrocellulose | | |
| 3-01-041-01 | Reactor Pots | tons produced |
| 3-01-041-02 | H2SO4 Concentrators | tons produced |
| 3-01-041-03 | Boiling Tubs | tons produced |
| 3-01-041-99 | Other/Not Classified | tons produced |
| Adhesives | | |
| 3-01-050-01 | General/Compound Unknown | tons produced |
| Acetate Flake | | |
| 3-01-090-99 | Other/Not Classified | tons produced |
| [illegible] | | |
| 3-01-091-01 | Other/Not Classified | tons produced |
| Malaic Anhydride | | |
| 3-01-100-01 | General/Other | tons produced |
| Polyvinyl Pyrillidon | | |
| 3-01-101-01 | General/Other | tons produced |
| Sulfonic Acid/ATS | | |
| 3-01-110-01 | General/Other | tons produced |
| Asbestos Chemical | | |
| 3-01-111-01 | Caulking | tons produced |
| 3-01-111-02 | Sealants | tons produced |
| 3-01-111-03 | Brake Line/Grinding | tons produced |
| 3-01-111-04 | Fire Proofing Manufacturing | tons produced |
| 3-01-111-99 | Others/Not Classified | tons produced |

## INDUSTRIAL PROCESS - CHEMICAL MANUFACTURING

| | | SCC Units |
|---|---|---|
| **Formaldehyde** | | |
| 3-01-120-01 | Silver Catalyst | tons produced |
| 3-01-120-02 | Mixed Oxide Catalyst | tons produced |
| **Ethylene Dichloride** | | |
| 3-01-125-01 | Oxychlorination | tons produced |
| 3-01-125-02 | Direct Chlorination | tons produced |
| **Ammonium Sulfate** | | |
| 3-01-130-01 | NH3-H2SO4 Process | tons produced |
| 3-01-130-02 | Coke Oven By-Product | tons produced |
| 3-01-130-03 | Caprolactamtion By-Product | tons produced |
| **Waste Gas Flares** | | |
| 3-01-900-99 | Other/Not Classified | million cubic feet burned |
| **Other/Not Classified** | | |
| 3-01-999-99 | Specify in Remark | tons produced |

## INDUSTRIAL PROCESS - FOOD/AGRICULTURAL

| | | SCC Units |
|---|---|---|
| Alfalfa Dehydrogenation | | |
| 3-02-001-01 | General | tons meal produced |
| 3-02-001-99 | Other/Not Classified | tons produced |
| Coffee Roasting | | |
| 3-02-002-01 | Direct Fire Roaster | tons green beans |
| 3-02-002-02 | Indirect Fire Roaster | tons green beans |
| 3-02-002-03 | Stoner/Cooler | tons green beans |
| 3-02-002-99 | Other/Not Classified | tons produced |
| Coffee-Instant | | |
| 3-02-003-01 | Spray Drier | tons green beans |
| Cotton Ginning | | |
| 3-02-004-01 | Unloading Fan | bales cotton |
| 3-02-004-02 | Cleaner | bales cotton |
| 3-02-004-03 | Stick/Burr Machine | bales cotton |
| 3-02-004-99 | Other/Not Classified | bales cotton |
| Feed/Grain Terminal | | |
| 3-02-005-01 | Shipping/Receiving | tons grain processed |
| 3-02-005-02 | Transfer/Conveying | tons grain processed |
| 3-02-005-03 | Screening/Cleaning | tons grain processed |
| 3-02-005-04 | Drying | tons grain processed |
| Feed/Grain Country Elevators | | |
| 3-02-006-01 | Shipping/Receiving | tons grain processed |
| 3-02-006-02 | Transfer/Conveying | tons grain processed |
| 3-02-006-03 | Screening/Cleaning | tons grain processed |
| 3-02-006-04 | Drying | tons grain processed |
| 3-02-006-99 | Other/Not Classified | tons grain processed |
| Grain Processing | | |
| 3-02-007-01 | Corn Meal | tons grain processed |
| 3-02-007-02 | Soy Bean Processing | tons grain processed |
| 3-02-007-03 | Barley/Wheat Cleaner | tons grain processed |
| 3-02-007-04 | Milo Cleaner | tons grain processed |
| 3-02-007-05 | Barley Flour Milling | tons grain processed |
| 3-02-007-06 | Wet Corn Milling | tons produced |
| 3-02-007-30 | Wheat Flour Milling | tons produced |
| 3-02-007-99 | Other/Not Classified | tons processed |

## INDUSTRIAL PROCESS - FOOD/AGRICULTURAL

### Feed Manufacture

| | | SCC Units |
|---|---|---|
| 3-02-008-01 | Barley Feed-General | tons grain processed |
| 3-02-008-99 | Other/Not Classified | tons processed |

### Fermentation-Beer

| | | |
|---|---|---|
| 3-02-009-01 | Grain Handling | tons grain processed |
| 3-02-009-02 | Drying Spent Grain | tons grain processed |
| 3-02-009-03 | Brewing | thousands of gallons |
| 3-02-009-98 | Other/Not Classified | gallons produced |
| 3-02-009-99 | Other/Not Classified | tons grain processed |

### Fermentation-Whiskey

| | | |
|---|---|---|
| 3-02-010-01 | Grain Handling | tons grain processed |
| 3-02-010-02 | Drying Spent Grain | tons grain processed |
| 3-02-010-03 | Aging | barrel (50 gallon) |
| 3-02-010-99 | Other/Not Classified | gallons produced |

### Fermentation-Wine

| | | |
|---|---|---|
| 3-02-011-01 | General | gallons produced |

### Fish Meal

| | | |
|---|---|---|
| 3-02-012-01 | Cookers-Fresh Fish | tons fish meal produced |
| 3-02-012-02 | Cookers-Stale Fish | tons fish meal produced |
| 3-02-012-03 | Driers | tons fish scrap |
| 3-02-012-99 | Other/Not Classified | tons processed |

### Meat Smoking

| | | |
|---|---|---|
| 3-02-013-01 | General | tons meat smoked |

### Starch Manufacturing

| | | |
|---|---|---|
| 3-02-014-01 | General | tons starch produced |

### Sugar Cane Processing

| | | |
|---|---|---|
| 3-02-015-01 | General | tons sugar produced |
| 3-02-015-99 | Other/Not Classified | tons processed |

### Sugar Beet Processing

| | | |
|---|---|---|
| 3-02-016-01 | Dryer Only | tons raw beets |
| 3-02-016-99 | Other/Not Classified | tons raw beets |

## INDUSTRIAL PROCESS - FOOD/AGRICULTURAL

| | | SCC Units |
|---|---|---|
| Peanut Processing | | |
| 3-02-017-20 | Oil/Not Classified | tons produced |
| 3-02-017-99 | Other/Not Classified | tons processed |
| Candy/Confectionary | | |
| 3-02-018-99 | Other/Not Classified | tons produced |
| Dairy Products | | |
| 3-02-030-01 | Milk Spray-Dryer | tons produced |
| 3-02-030-99 | Other/Not Classified | tons produced |
| Other/Not Classified | | |
| 3-02-999-98 | Specify in Remark | tons processed (input) |
| 3-02-999-99 | Specify in Remark | tons produced (finished) |

Subject: Source Classification
Codes (SCC)

## INDUSTRIAL PROCESS - PRIMARY METALS

| | | SCC Units |
|---|---|---|
| Aluminum Ore-Bauxite | | |
| 3-03-000-01 | Crushing/Handling | tons of ore |
| Aluminum Ore-Electrolytic Reduction | | |
| 3-03-001-01 | Prebake Cells | tons aluminum produced |
| 3-03-001-02 | Horizontal-Stud Soderberg | tons aluminum produced |
| 3-03-001-03 | Vertical-Stud Soderberg | tons aluminum produced |
| 3-03-001-04 | Materials Handling | tons aluminum produced |
| 3-03-001-05 | Anode Bake Furnace | tons aluminum produced |
| 3-03-001-99 | Other/Not Classified | tons aluminum produced |
| Aluminum Ore-Calcining Aluminum hydroxide | | |
| 3-03-002-01 | General | tons aluminum produced |
| Coke Metallurgical By-Product | | |
| 3-03-003-01 | General | tons coal charged |
| 3-03-003-02 | Oven Charging | tons coal charged |
| 3-03-003-03 | Oven Pushing | tons coal charged |
| 3-03-003-04 | Quenching | tons coal charged |
| 3-03-003-05 | Unloading | tons coal charged |
| 3-03-003-06 | Underfiring | tons coal charged |
| 3-03-003-07 | Coal Crushing/Handling | tons coal charged |
| 3-03-003-99 | Other/Not Classified | tons coal charged |
| Coke Metallurgical-Beehive | | |
| 3-03-004-01 | General | tons coal charged |
| Copper Smelter | | |
| 3-03-005-01 | Total/General | tons concentrated ore |
| 3-03-005-02 | Roasting | tons concentrated ore |
| 3-03-005-03 | Smelting | tons concentrated ore |
| 3-03-005-04 | Converting | tons concentrated ore |
| 3-03-005-05 | Refining | tons concentrated ore |
| 3-03-005-06 | Ore Dryer | tons of ore |
| 3-03-005-08 | Finish Operation-General | tons produced |
| 3-03-005-99 | Other/Not Classified | tons concentrated ore |
| Ferroalloy Open Furnace | | |
| 3-03-006-01 | 50% Ferrosilicon | tons produced |
| 3-03-006-02 | 75% Ferrosilicon | tons produced |
| 3-03-006-03 | 90% Ferrosilicon | tons produced |
| 3-03-006-04 | Silicon Metal | tons produced |
| 3-03-006-05 | Silicon Manganese | tons produced |

## INDUSTRIAL PROCESS - PRIMARY METALS

### Ferroalloy Open Furnace (continued)

| | | SCC Units |
|---|---|---|
| 3-03-006-10 | Screening | tons processed |
| 3-03-006-11 | Ore Dryer | tons processed |
| 3-03-006-12 | Low Carbon Chromium-Reactor | tons processed |
| 3-03-006-99 | Other/Not Classified | tons produced |

### Ferroalloy Semi-Covered Furnace

| | | |
|---|---|---|
| 3-03-007-01 | Ferromanganese | tons produced |
| 3-03-007-02 | General | tons produced |

### Iron Production

| | | |
|---|---|---|
| 3-03-008-01 | Blast Furnace-Ore Charging | tons produced |
| 3-03-008-02 | Blast Furnace-Agglomerates Charging | tons produced |
| 3-03-008-03 | Sintering General | tons produced |
| 3-03-008-04 | Ore-Crushing and Handling | tons of ore |
| 3-03-008-05 | Scarfing | tons processed |
| 3-03-008-06 | Sand Handling Open | tons handled |
| 3-03-008-07 | Mold Ovens | tons sand baked |
| 3-03-008-08 | Slag Crushing and Handling | tons handled |
| 3-03-008-99 | Other/Not Classified | tons produced |

### Steel Production

| | | |
|---|---|---|
| 3-03-009-01 | Open Hearth Oxygen Lance | tons produced |
| 3-03-009-02 | Open Hearth No Oxygen Lance | tons produced |
| 3-03-009-03 | Basic Oxygen Furnace - General | tons produced |
| 3-03-009-04 | Electric Arc with Lance | tons produced |
| 3-03-009-05 | Electric Arc no Lance | tons produced |
| 3-03-009-10 | Finishing and Pickling | tons produced |
| 3-03-009-11 | Finishing and Soaking Pits | tons produced |
| 3-03-009-12 | Finishing and Grinding, etc. | tons produced |
| 3-03-009-20 | Finishing and Other | tons produced |
| 3-03-009-99 | Other/Not Classified | tons produced |

### Lead Shelters

| | | |
|---|---|---|
| 3-03-010-01 | Sintering | tons concentrated ore |
| 3-03-010-02 | Blast Furnace | tons concentrated ore |
| 3-03-010-03 | Reverberatory Furnace | tons concentrated ore |
| 3-03-010-04 | Ore Crushing | tons of ore crushed |
| 3-03-010-05 | Materials Handling | tons of lead produced |
| 3-03-010-99 | Other/Not Classified | tons concentrated ore |

### Molybdenum

| | | |
|---|---|---|
| 3-03-011-01 | Mining-General | hundreds of tons mined |
| 3-03-011-02 | Milling-General | tons produced |
| 3-03-011-99 | Processing-Other | tons processed |

## INDUSTRIAL PROCESS - PRIMARY METALS

| | | SCC Units |
|---|---|---|
| **Titanium Process** | | |
| 3-03-012-01 | Chlorination Station | tons produced |
| 3-03-012-99 | Other/Not Classified | tons processed |
| **Gold** | | |
| 3-03-013-01 | Mining and Processing | tons ore |
| **Barium** | | |
| 3-03-014-01 | Ore Grinding | tons processed |
| 3-03-014-02 | Reduction Kiln | tons processed |
| 3-03-014-03 | Driers and Calciners | tons processed |
| 3-03-014-99 | Other/Not Classified | tons processed |
| **Beryllium Ore** | | |
| 3-03-015-01 | Storage | tons of ore |
| 3-03-015-02 | Crushing | tons processed |
| 3-03-015-03 | Melting | tons processed |
| 3-03-015-04 | Quenching and Heat Treating | tons processed |
| 3-03-015-05 | Grinding | tons processed |
| 3-03-015-06 | Sulfation and Dissolvation | tons processed |
| 3-03-015-07 | Sintering | tons processed |
| 3-03-015-08 | Ventilation | tons processed |
| 3-03-015-09 | Leach and Filter | tons processed |
| 3-03-015-99 | Other/Not Classified | tons processed |
| **Mercury Mining** | | |
| 3-03-025-01 | Surface Blasting | tons of ore |
| 3-03-025-02 | Surface Drilling | tons of ore |
| 3-03-025-03 | Surface Handling | tons of ore |
| 3-03-025-04 | Natural Vapor | tons of ore |
| 3-03-025-05 | Stripping | tons removed |
| 3-03-025-06 | Loading | tons of ore |
| 3-03-025-07 | Conveying and Hauling | tons of ore |
| 3-03-025-08 | Unloading | tons of ore |
| 3-03-025-09 | Conveying and Hauling Waste | tons of ore |
| 3-03-025-99 | Other/Not Classified | tons of ore |
| **Mercury Ore Processes** | | |
| 3-03-026-01 | Crushing | tons processed |
| 3-03-026-02 | Rotary Furnace | tons processed |
| 3-03-026-03 | Retort Furnace | tons processed |
| 3-03-026-04 | Calcining | tons processed |
| 3-03-026-05 | Burnt Ore Bin | tons processed |
| 3-03-026-06 | Hoeing Process | tons processed |
| 3-03-026-99 | Other/Not Classified | tons processed |

## INDUSTRIAL PROCESS - PRIMARY METALS

### Zinc Smelting

| | | SCC Units |
|---|---|---|
| 3-03-030-01 | General | tons processed |
| 3-03-030-02 | Roasting and Multiple-Hearth | tons processed |
| 3-03-030-03 | Sintering | tons processed |
| 3-03-030-04 | Horizontal Retorts | tons processed |
| 3-03-030-05 | Vertical Retorts | tons processed |
| 3-03-030-06 | Electrolytic Process | tons processed |
| 3-03-030-99 | Other/Not Classified | tons processed |

### Other/Not Classified

| | | |
|---|---|---|
| 3-03-999-99 | Specify in Remark | tons produced |

## INDUSTRIAL PROCESS - SECONDARY METALS

### Aluminum Operation

| | | SCC Units |
|---|---|---|
| 3-04-001-01 | Sweating Furnace | tons produced |
| 3-04-001-02 | Smelting-Crucible | tons metal produced |
| 3-04-001-03 | Smelting-Reverberatory Furnace | tons metal produced |
| 3-04-001-04 | Chlorination Station | tons metal produced |
| 3-04-001-10 | Foil Rolling | tons produced |
| 3-04-001-11 | Foil Converting | tons produced |
| 3-04-001-20 | Can Manufacturing | tons produced |
| 3-04-001-50 | Rolling-Drawing-Extruding | tons produced |
| 3-04-001-99 | Other/Not Classified | tons produced |

### Brass and Bronz Melting

| | | |
|---|---|---|
| 3-04-002-01 | Blast Furnace | tons charged |
| 3-04-002-02 | Crucible Furnace | tons charged |
| 3-04-002-03 | Cupola Furnace | tons charged |
| 3-04-002-04 | Electric Induction Furnace | tons charged |
| 3-04-002-05 | Reverberatory Furnace | tons charged |
| 3-04-002-06 | Rotary Furnace | tons charged |
| 3-04-002-99 | Other/Not Classified | tons produced |

### Gray Iron

| | | |
|---|---|---|
| 3-04-003-01 | Cupola Furnace | tons metal charged |
| 3-04-003-02 | Reverberatory Furnace | tons metal charged |
| 3-04-003-03 | Electric Induction Furnace | tons metal charged |
| 3-04-003-05 | Annealing Operation | tons metal charged |
| 3-04-003-30 | Miscellaneous Casting-Fabrication | tons processed |
| 3-04-003-40 | Grinding-Cleaning | tons processed |
| 3-04-003-50 | Sand Handling-General | tons handled |
| 3-04-003-99 | Other/Not Classified | tons metal charged |

### Lead Smelting Secondary

| | | |
|---|---|---|
| 3-04-004-01 | Pot Furnace | tons metal charged |
| 3-04-004-02 | Reverberatory Furnace | tons metal charged |
| 3-04-004-03 | Blasting and Cupola Furnace | tons metal charged |
| 3-04-004-04 | Rotary Reverberatory Furnace | tons metal charged |
| 3-04-004-08 | Lead Oxide Manufacturing | tons processed |
| 3-04-004-99 | Other/Not Classified | tons processed |

### Lead Battery

| | | |
|---|---|---|
| 3-04-005-01 | Total-General | tons of batteries produced |
| 3-04-005-02 | Casting Furnace | tons of batteries produced |
| 3-04-005-03 | Paste Mixer | tons of batteries produced |
| 3-04-005-04 | Three Process Operation | tons of batteries produced |
| 3-04-005-99 | Other/Not Classified | tons processed |

## INDUSTRIAL PROCESS - SECONDARY METALS

| Magnesium Secondary | | SCC Units |
|---|---|---|
| 3-04-006-01 | Pot Furnace | tons processed |
| 3-04-006-99 | Other/Not Classified | tons processed |
| Steel Foundry | | |
| 3-04-007-01 | Electric Arc Furnace | tons processed |
| 3-04-007-02 | Open Hearth Furnace | tons processed |
| 3-04-007-03 | Open Hearth Oxygen Lanced | tons processed |
| 3-04-007-04 | Heat-Treating Furnace | tons processed |
| 3-04-007-05 | Electric Induction Furnace | tons processed |
| 3-04-007-06 | Sand Grinding and Handling | tons handled |
| 3-04-007-10 | Finishing and Soaking Pits | tons processed |
| 3-04-007-15 | Finishing/Not Classified | tons processed |
| 3-04-007-99 | Other/Not Classified | tons processed |
| Zinc Secondary | | |
| 3-04-008-01 | Retort Furnace | tons produced |
| 3-04-008-02 | Horizontal Muffle Furnace | tons produced |
| 3-04-008-03 | Pot Furnace | tons produced |
| 3-04-008-04 | Kettle-Sweating Furnace | tons produced |
| 3-04-008-05 | Galvanizing Kettle | tons produced |
| 3-04-008-06 | Calcining Kiln | tons produced |
| 3-04-008-07 | Concentrating Drier | tons processed |
| 3-04-008-08 | Reverberatory-Sweating Furnace | tons produced |
| 3-04-008-99 | Other/Not Classified | tons processed |
| Malleable Iron | | |
| 3-04-009-01 | Annealing Operation | tons metal charged |
| 3-04-009-99 | Other/Not Classified | tons metal charged |
| Nickel | | |
| 3-04-010-01 | Flux Furnace | tons processed |
| 3-04-010-99 | Other/Not Classified | tons processed |
| Zirconium | | |
| 3-04-011-01 | Oxide Kiln | tons processed |
| 3-04-011-99 | Other/Not Classified | tons processed |
| Furnace Electrode | | |
| 3-04-020-01 | Calcination | tons processed |
| 3-04-020-02 | Mixing | tons processed |
| 3-04-020-03 | Pitch Treating | tons processed |
| 3-04-020-04 | Baking Furnace | tons processed |
| 3-04-020-99 | Other/Not Classified | tons processed |

## INDUSTRIAL PROCESS - SECONDARY METALS

|  | SCC Units |
|---|---|
| Miscellaneous Casting and Fabrication |  |
| 3-04-050-01 Specify in Remark | tons produced |
| Other/Not Classified |  |
| 3-04-999-99 Specify in Remark | tons processed |

## INDUSTRIAL PROCESS - MINERAL PRODUCTS

### Asphalt Roofing

| | | SCC Units |
|---|---|---|
| 3-05-001-01 | Blowing Operation | tons saturated felt proc |
| 3-05-001-02 | Dipping Only | tons saturated felt proc |
| 3-05-001-03 | Spraying Only | tons saturated felt proc |
| 3-05-001-04 | Dipping and Spraying | tons saturated felt proc |
| 3-05-001-99 | Other/Not Classified | tons saturated felt proc |

### Asphaltic Concrete

| | | |
|---|---|---|
| 3-05-002-01 | Rotary Drier | tons produced |
| 3-05-002-02 | Other Sources | tons produced |
| 3-05-002-99 | Other/Not Classified | tons produced |

### Brick Manufacture

| | | |
|---|---|---|
| 3-05-003-01 | Drying-Raw Material | tons produced |
| 3-05-003-02 | Grinding-Raw Material | tons produced |
| 3-05-003-03 | Storage-Raw Material | tons produced |
| 3-05-003-04 | Curing Gas Fired | tons produced |
| 3-05-003-05 | Curing Oil Fired | tons produced |
| 3-05-003-06 | Curing Coal Fired | tons produced |
| 3-05-003-99 | Other/Not Classified | tons produced |

### Calcium Carbide

| | | |
|---|---|---|
| 3-05-004-01 | Electric Furnace | tons produced |
| 3-05-004-02 | Coke Drier | tons produced |
| 3-05-004-03 | Furnace Room Vents | tons produced |
| 3-05-004-99 | Other/Not Classified | tons processed |

### Castable Refractories

| | | |
|---|---|---|
| 3-05-005-01 | Raw Material Drier | tons feed material |
| 3-05-005-02 | Raw Material Crushing and Processing | tons feed material |
| 3-05-005-03 | Electric Arc Melting | tons feed material |
| 3-05-005-04 | Curing Oven | tons feed material |
| 3-05-005-05 | Molding and Shakeout | tons feed material |
| 3-05-005-99 | Other/Not Classified | tons feed material |

### Cement Manufacture Dry

| | | |
|---|---|---|
| 3-05-006-01 | Kilns | barrels cement produced |
| 3-05-006-02 | Driers and Grinders, etc. | barrels cement produced |
| 3-05-006-03 | Kilns-Oil Fired | tons cement produced |
| 3-05-006-04 | Kilns-Gas Fired | tons cement produced |
| 3-05-006-05 | Kilns-Coal Fired | tons cement produced |
| 3-05-006-99 | Other/Not Classified | tons cement produced |

## INDUSTRIAL PROCESS - MINERAL PRODUCTS

| | | SCC Units |
|---|---|---|
| Cement Manufacture Wet | | |
| 3-05-007-01 | Kilns | barrels cement produced |
| 3-05-007-02 | Driers and Grinders, etc. | barrels cement produced |
| 3-05-007-03 | Kilns-Oil Fired | tons cement produced |
| 3-05-007-04 | Kilns-Gas Fired | tons cement produced |
| 3-05-007-05 | Kilns-Coal Fired | tons cement produced |
| 3-05-007-99 | Other/Not Classified | tons cement produced |
| Ceramic and Clay Manufacture | | |
| 3-05-008-01 | Drying | tons input to process |
| 3-05-008-02 | Grinding | tons input to process |
| 3-05-008-03 | Storage | tons input to process |
| 3-05-008-99 | Other/Not Classified | tons produced |
| Clay and Fly Ash Sinter | | |
| 3-05-009-01 | Fly Ash | tons finished product |
| 3-05-009-02 | Clay and Coke | tons finished product |
| 3-05-009-03 | Natural Clay | tons finished product |
| 3-05-009-99 | Other/Not Classified | tons produced |
| Coal Cleaning | | |
| 3-05-010-01 | Thermal and Fluidized Bed | tons coal dried |
| 3-05-010-02 | Thermal and Flash | tons coal dried |
| 3-05-010-03 | Thermal and Multilouvered | tons coal dried |
| 3-05-010-99 | Other/Not Classified | tons coal cleaned |
| Concrete Batching | | |
| 3-05-011-01 | General | cubic yards concrete produced |
| 3-05-011-20 | Asbestos and Cement Products | tons produced |
| 3-05-011-21 | Road Surface | tons produced |
| 3-05-011-99 | Other/Not Classified | tons produced |
| Fiberglass Manufacture | | |
| 3-05-012-01 | Reverberatory Furnace-Regenerative | tons material processed |
| 3-05-012-02 | Reverberatory Furnace-Recuperative | tons material processed |
| 3-05-012-03 | Electric Induction Furnace | tons material processed |
| 3-05-012-04 | Forming Line | tons material processed |
| 3-05-012-05 | Curing Oven | tons material processed |
| 3-05-012-99 | Other/Not Classified | tons processed |
| Frit Manufacture | | |
| 3-05-013-01 | Rotary Furnace General | tons charged |
| 3-05-013-99 | Other/Not Classified | tons charged |

## INDUSTRIAL PROCESS - MINERAL PRODUCTS

### Glass Manufacture

| | | SCC Units |
|---|---|---|
| 3-05-014-01 | Soda-Lime General Furnace | tons glass produced |
| 3-05-014-10 | Raw Material Recovery and Storage | tons processed |
| 3-05-014-11 | Batching and Mixing | tons processed |
| 3-05-014-12 | Molten Holding Tanks | tons processed |
| 3-05-014-99 | Other/Not Classified | tons produced |

### Gypsum Manufacture

| | | |
|---|---|---|
| 3-05-015-01 | Raw Material Drier | tons throughput |
| 3-05-015-02 | Primary Grinder | tons throughput |
| 3-05-015-03 | Calciner | tons throughput |
| 3-05-015-04 | Conveying | tons throughput |
| 3-05-015-99 | Other/Not Classified | tons throughput |

### Lime Manufacture

| | | |
|---|---|---|
| 3-05-016-01 | Primary Crushing | tons processed |
| 3-05-016-02 | Secondary Crushing | tons processed |
| 3-05-016-03 | Calcining-Vertical Kiln | tons processed |
| 3-05-016-04 | Calcining-Rotary Kiln | tons processed |
| 3-05-016-05 | Calcimatic Kiln | tons processed |
| 3-05-016-06 | Fluidized Bed Kiln | tons processed |
| 3-05-014-09 | Hydrator | tons hydrated lime prod |
| 3-05-014-99 | Other/Not Classified | tons processed |

### Mineral Wool

| | | |
|---|---|---|
| 3-05-017-01 | Cupola | tons charged |
| 3-05-017-02 | Reverberatory Furnace | tons charged |
| 3-05-017-03 | Blow Chamber | tons charged |
| 3-05-017-04 | Curing Oven | tons charged |
| 3-05-017-05 | Cooler | tons charged |
| 3-05-017-99 | Other/Not Classified | tons processed |

### Perlite Manufacture

| | | |
|---|---|---|
| 3-05-018-01 | Vertical Furnace General | tons charged |
| 3-05-018-99 | Other/Not Classified | tons processed |

### Phosphate Rock

| | | |
|---|---|---|
| 3-05-019-01 | Drying | tons phosphate rock |
| 3-05-019-02 | Grinding | tons phosphate rock |
| 3-05-019-03 | Transfer and Storage | tons phosphate rock |
| 3-05-019-04 | Open and Storage | tons phosphate rock |
| 3-05-019-99 | Other/Not Classified | tons processed |

## INDUSTRIAL PROCESS - MINERAL PRODUCTS

| Stone Quarrying and Processing | | SCC Units |
|---|---|---|
| 3-05-020-01 | Primary Crushing | tons raw material |
| 3-05-020-02 | Secondary Crushing and Screening | tons raw material |
| 3-05-020-03 | Tertiary Crushing and Screening | tons raw material |
| 3-05-020-04 | Recrushing and Screening | tons raw material |
| 3-05-020-05 | Fines Mill | tons raw material |
| 3-05-020-06 | Screening, Conveying and Handling | tons produced |
| 3-05-020-07 | Open Storage | tons produced stored |
| 3-05-020-08 | Cutting Stone-General | tons processed |
| 3-05-020-09 | Blasting-General | tons processed |
| 3-05-020-99 | Other/Not Classified | tons processed |
| Salt Mining | | |
| 3-05-021-01 | General | tons mined |
| Potash Production | | |
| 3-05-022-01 | Mining-Grinding and Drying | tons ore |
| 3-05-022-99 | Other/Not Classified | tons processed |
| Calcium Borate | | |
| 3-05-023-01 | Mining and Processing | tons produced |
| 3-05-023-99 | Other/Not Classified | tons processed |
| Magnesium Carbonate | | |
| 3-05-024-01 | Mining and Processing | tons produced |
| 3-05-024-99 | Other/Not Classified | tons processed |
| Sand and Gravel | | |
| 3-05-025-01 | Crushing and Screening | tons produced |
| 3-05-025-99 | Other/Not Classified | tons processed |
| Diatomacous Earth | | |
| 3-05-026-01 | Handling | tons produced |
| 3-05-026-99 | Other/Not Classified | tons processed |
| Ceramic Electrical Products | | |
| 3-05-030-99 | Other/Not Classified | tons processed |

## INDUSTRIAL PROCESS - MINERAL PRODUCTS

### Asbestos Mining

| | | SCC Units |
|---|---|---|
| 3-05-031-01 | Surface Blasting | tons of ore |
| 3-05-031-02 | Surface Drilling | tons of ore |
| 3-05-031-03 | Cobbing | tons of ore |
| 3-05-031-04 | Loading | tons of ore |
| 3-05-031-05 | Conveying and Hauling Asbestos | tons of ore |
| 3-05-031-06 | Conveying and Hauling Waste | tons of ore |
| 3-05-031-07 | Unloading | tons of ore |
| 3-05-031-08 | Stripping | tons removed |
| 3-05-031-09 | Ventilation | tons of ore |
| 3-05-031-10 | Stockpiling | tons of ore |
| 3-05-031-11 | Tailings | tons of material |
| 3-05-031-99 | Other/Not Classified | tons processed |

### Asbestos Milling

| | | |
|---|---|---|
| 3-05-032-01 | Crushing | tons processed |
| 3-05-032-02 | Drying | tons processed |
| 3-05-032-03 | Recrushing | tons processed |
| 3-05-032-04 | Screening | tons processed |
| 3-05-032-05 | Fiberizing | tons processed |
| 3-05-032-06 | Bagging | tons processed |
| 3-05-032-99 | Other/Not Classified | tons processed |

### Mining-Special Material

| | | |
|---|---|---|
| 3-05-040-01 | Open Pit-Blasting | tons of material |
| 3-05-040-02 | Open Pit-Drilling | tons of material |
| 3-05-040-03 | Open Pit-Cobbing | tons of material |
| 3-05-040-10 | Underground Ventilation | tons of material |
| 3-05-040-20 | Loading | tons of material |
| 3-05-040-21 | Conveying and Hauling Material | tons of material |
| 3-05-040-22 | Conveying and Hauling Waste | tons of material |
| 3-05-040-23 | Unloading | tons of material |
| 3-05-040-24 | Stripping | tons of material |
| 3-05-040-25 | Stockpile | tons of material |
| 3-05-040-30 | Primary Crusher | tons of material |
| 3-05-040-31 | Secondary Crusher | tons of material |
| 3-05-040-32 | Ore Concentrator | tons of material |
| 3-05-040-33 | Ore Drier | tons of material |
| 3-05-040-34 | Screening | tons of material |
| 3-05-040-36 | Tailing Piles | tons of material |
| 3-05-040-99 | Other/Not Classified | tons of material |

### Other/Not Classified

| | | |
|---|---|---|
| 3-05-999-99 | Specify in Remark | tons produced |

## INDUSTRIAL PROCESS - PETROLEUM INDUSTRY

| | | SCC Units |
|---|---|---|
| Process Heater | | |
| 3-06-001-01 | Oil | 1000 barrels oil burned |
| 3-06-001-02 | Gas | 1000 cubic feet gas burned |
| 3-06-001-03 | Oil | 1000 gallons oil burned |
| 3-06-001-04 | Gas | million cubic feet burned |
| Fluid Cracking | | |
| 3-06-002-01 | General (Fluidized-bed Catalytic Cracking) | 1000 barrels fresh feed |
| Moving-Bed Catalytic Cracking | | |
| 3-06-003-01 | General (Thermofor Catalytic Cracking) | 1000 barrels fresh feed |
| Blowdown System | | |
| 3-06-004-01 | With Controls | 1000 barrels refinery capacity |
| 3-06-004-02 | Without Controls | 1000 barrels refinery capacity |
| Process Drains | | |
| 3-06-005-01 | General With Controls | 1000 barrels waste water |
| 3-06-005-02 | General Without Controls | 1000 barrels waste water |
| Vacuum Jets | | |
| 3-06-006-01 | With Controls | 1000 barrels vacuum distillation |
| 3-06-006-02 | Without Controls | |
| Cooling Towers | | |
| 3-06-007-01 | | million gallons cooling water |
| Miscellaneous | | |
| 3-06-008-01 | Pipe and Valve-Flange | 1000 barrels refinery capacity |
| 3-06-008-02 | Vessel Relief Valve | 1000 barrels refinery capacity |
| 3-06-008-03 | Pump Seals | 1000 barrels refinery capacity |
| 3-06-008-04 | Compressor Seals | 1000 barrels refinery capacity |
| 3-06-008-05 | Other-General | 1000 barrels refinery capacity |
| Flares | | |
| 3-06-009-01 | Natural Gas | millions of cubic feet |
| 3-06-009-99 | Other/Not Classified | millions of cubic feet |
| Sludge Converter | | |
| 3-06-010-01 | General | tons processed |

INDUSTRIAL PROCESS - PETROLEUM INDUSTRY

| | | SCC Units |
|---|---|---|
| Asphalt Oxidizer | | |
| 3-06-011-01 | General | tons processed |
| 3-06-011-99 | Other/Not Classified | tons processed |
| Fluid Coking | | |
| 3-06-012-01 | General | 1000 barrels fresh feed |
| 3-06-012-02 | Cooling Operation | 1000 barrels fresh feed |
| 3-06-012-03 | Transportation | 1000 barrels fresh feed |
| 3-06-012-04 | Storage | 1000 barrels fresh feed |
| Catalytic Reforming | | |
| 3-06-013-01 | General | 1000 barrels fresh feed |
| Other/Not Classified | | |
| 3-06-999-98 | Specify in Remark | tons processed |
| 3-06-999-99 | Specify in Remark | barrels processed |

## INDUSTRIAL PROCESS - WOOD PRODUCTS

### Sulfate Pulping

| | | SCC Units |
|---|---|---|
| 3-07-001-01 | Blow Tank Accumulator | air-dry tons unbleached pulp |
| 3-07-001-02 | Washings and Screenings | air-dry tons unbleached pulp |
| 3-07-001-03 | Multi-Effect Evaperator | air-dry tons unbleached pulp |
| 3-07-001-04 | Recovery Boiler & Direct Contact Evaperator -- | air-dry tons unbleached pulp |
| 3-07-001-05 | Smelting Dissolving Tank | air-dry tons unbleached pulp |
| 3-07-001-06 | Lime Kilns | air-dry tons unbleached pulp |
| 3-07-001-07 | Turpentine Condenser | air-dry tons unbleached pulp |
| 3-07-001-08 | Fluid Bed Calciner | air-dry tons unbleached pulp |
| 3-07-001-09 | Liquor Oxidation Tower | air-dry tons unbleached pulp |
| 3-07-001-99 | Other/Not Classified | air-dry tons unbleached pulp |

### Sulfite Pulping

| | | |
|---|---|---|
| 3-07-002-01 | Liquor Recovery | air-dry tons unbleached pulp |
| 3-07-002-02 | Sulfite Tower | air-dry tons unbleached pulp |
| 3-07-002-03 | Digester | air-dry tons unbleached pulp |
| 3-07-002-04 | Smelting Tank | air-dry tons unbleached pulp |
| 3-07-002-05 | Evaporators | air-dry tons unbleached pulp |
| 3-07-002-06 | Pulp Digester | tons air dry pulp |
| 3-07-002-99 | Other/Not Classified | tons air dry pulp |

### Pulpboard Manufacture

| | | |
|---|---|---|
| 3-07-004-01 | Paperboard-General | tons finished produced |
| 3-07-004-02 | Fiberboard-General | tons finished produced |
| 3-07-004-99 | Other/Not Classified | tons finished produced |

### Pressure Treating

| | | |
|---|---|---|
| 3-07-005-01 | Creosote | tons of wood treated |
| 3-07-005-99 | Other/Not Classified | tons of wood treated |

### Tall Oil and Rosin

| | | |
|---|---|---|
| 3-07-006-01 | General | tons of product |

### Plywood and Particle Board

| | | |
|---|---|---|
| 3-07-007-01 | Veneer Dryer | tons processed |
| 3-07-007-02 | Sanding | tons processed |
| 3-07-007-99 | Other/Not Classified | tons processed |

### Sawmill Operations

| | | |
|---|---|---|
| 3-07-008-99 | Other/Not Classified | tons processed |

INDUSTRIAL PROCESS - WOOD PRODUCTS

| | SCC Units |
|---|---|
| Excelsior Manufacture | |
| 3-07-009-99 Other/Not Classified | tons processed |
| Cork Processing | |
| 3-07-010-99 Other/Not Classified | tons processed |
| Furniture Manufacture | |
| 3-07-020-99 Other/Not Classified | tons processed |
| Other/Not Classified | |
| 3-07-999-99 Specify in Remark | tons processed |

## INDUSTRIAL PROCESS - METAL FABRICATION

| | | SCC Units |
|---|---|---|
| Iron and Steel | | |
| 3-09-001-01 | Miscellaneous Hardware | tons of product |
| 3-09-001-02 | Farm Machinery | tons of product |
| 3-09-001-99 | Other/Not Classified | tons processed |
| Plating Operations | | |
| 3-09-010-99 | Other/Not Classified | tons plated |
| Can Making Operations | | |
| 3-09-020-99 | Other/Not Classified | tons produced |
| Machine Operations | | |
| 3-09-030-01 | Drilling-Special Material | tons processed |
| 3-09-030-02 | Milling-Special Material | tons processed |
| 3-09-030-03 | Reaming-Special Material | tons processed |
| 3-09-030-04 | Grinding-Special Material | tons processed |
| 3-09-030-05 | Sawing-Special Material | tons processed |
| 3-09-030-06 | Honing-Special Material | tons processed |
| 3-09-030-99 | Other-Special Material | tons processed |
| Other/Not Classified | | |
| 3-09-999-99 | Specify in Remark | tons processed |

## INDUSTRIAL PROCESS - LEATHER PRODUCTS

| Other/Not Classified | SCC Units |
|---|---|
| 3-20-999-99 Specify in Remark | tons processed |

## INDUSTRIAL PROCESS - TEXTILE MANUFACTURE

| General Fabrics | | SCC Units |
|---|---|---|
| 3-30-001-01 | Yarn Preparing and Bleaching | tons processed |
| 3-30-001-02 | Printing | tons processed |
| 3-30-001-99 | Other/Not Specified | tons processed |
| **Rubberized Fabric** | | |
| 3-30-002-01 | Impregnation | tons processed |
| 3-30-002-02 | Wet Coating | tons processed |
| 3-30-002-03 | Hot Melt Coating | tons processed |
| 3-30-002-99 | Other/Not Specified | tons processed |
| **Carpet Operations** | | |
| 3-30-003-99 | Other/Not Specified | tons processed |

## INDUSTRIAL PROCESS - INPROCESS FUEL

Anthracite Coal

| | | SCC Units |
|---|---|---|
| 3-90-001-99 | Other/Not Classified | tons burned |

Bituminous Coal

| | | |
|---|---|---|
| 3-90-002-01 | Cement Kiln and Dryer | tons burned |
| 3-90-002-03 | Lime Kiln | tons burned |
| 3-90-002-04 | Kaolin Kiln | tons burned |
| 3-90-002-06 | Brick Kiln and Dryer | tons burned |
| 3-90-002-07 | Gypsum Kiln, etc. | tons burned |
| 3-90-002-08 | Coal Dryers | tons burned |
| 3-90-002-09 | Rock and Gravel Dryer | tons burned |
| 3-90-002-99 | Other/Not Classified | tons burned |

Residual Oil

| | | |
|---|---|---|
| 3-90-004-01 | Asphalt Dryer | 1000 gallons burned |
| 3-90-004-02 | Cement Kiln and Dryer | 1000 gallons burned |
| 3-90-004-03 | Lime Kiln | 1000 gallons burned |
| 3-90-004-04 | Kaolin Kiln | 1000 gallons burned |
| 3-90-004-05 | Metal Melting | 1000 gallons burned |
| 3-90-004-06 | Brick Kiln and Dryer | 1000 gallons burned |
| 3-90-004-07 | Gypsum Kiln, etc. | 1000 gallons burned |
| 3-90-004-08 | Glass Furnace | 1000 gallons burned |
| 3-90-004-09 | Rock and Gravel Dryer | 1000 gallons burned |
| 3-90-004-10 | Frit Smelter | 1000 gallons burned |
| 3-90-004-11 | Perlite Furnace | 1000 gallons burned |
| 3-90-004-30 | Feed and Grain Drying | 1000 gallons burned |
| 3-90-004-31 | Food-Drying and Cooking, etc. | 1000 gallons burned |
| 3-90-004-32 | Fertilizer Drying | 1000 gallons burned |
| 3-90-004-50 | Pulpboard-Dryers | 1000 gallons burned |
| 3-90-004-51 | Plywood-dryers | 1000 gallons burned |
| 3-90-004-52 | Pulp-Recovery Boiler | 1000 gallons burned |
| 3-90-004-99 | Other/Not Classified | 1000 gallons burned |

Distillate Oil

| | | |
|---|---|---|
| 3-90-005-01 | Asphalt Dryer | 1000 gallons burned |
| 3-90-005-02 | Cement Kiln and Dryer | 1000 gallons burned |
| 3-90-005-03 | Lime Kiln | 1000 gallons burned |
| 3-90-005-04 | Kaolin Kiln | 1000 gallons burned |
| 3-90-005-05 | Metal Melting | 1000 gallons burned |
| 3-90-005-06 | Brick Kiln and Dryer | 1000 gallons burned |
| 3-90-005-07 | Gypsum Kiln, etc. | 1000 gallons burned |
| 3-90-005-08 | Glass Furnace | 1000 gallons burned |
| 3-90-005-09 | Rock and Gravel Dryer | 1000 gallons burned |
| 3-90-005-10 | Frit Smelter | 1000 gallons burned |
| 3-90-005-11 | Perlite Furnace | 1000 gallons burned |

## INDUSTRIAL PROCESS - INPROCESS FUEL

Distillate Oil (continued)

| | | SCC Units |
|---|---|---|
| 3-90-005-30 | Feed and Grain Drying | 1000 gallons burned |
| 3-90-005-31 | Food-Drying, Cooking, etc. | 1000 gallons burned |
| 3-90-005-32 | Fertilizer Drying | 1000 gallons burned |
| 3-90-005-50 | Pulpboard-dryers | 1000 gallons burned |
| 3-90-005-51 | Plywood-Dryers | 1000 gallons burned |
| 3-90-005-52 | Pulp-Recovery Boiler | 1000 gallons burned |
| 3-90-005-99 | Other/Not Classified | 1000 gallons burned |

Natural Gas

| | | |
|---|---|---|
| 3-90-006-01 | Asphalt Dryer | million cubic feet burned |
| 3-90-006-02 | Cement Kiln and Dryer | million cubic feet burned |
| 3-90-006-03 | Lime Kiln | million cubic feet burned |
| 3-90-006-04 | Kaolin Kiln | million cubic feet burned |
| 3-90-006-05 | Metal Melting | million cubic feet burned |
| 3-90-006-06 | Brick Kiln and Dryer | million cubic feet burned |
| 3-90-006-07 | Gypsum Kiln, etc. | million cubic feet burned |
| 3-90-006-08 | Glass Furnace | million cubic feet burned |
| 3-90-006-09 | Rock and Gravel Dryer | million cubic feet burned |
| 3-90-006-10 | Frit Smelter | million cubic feet burned |
| 3-90-006-11 | Perlite Furnace | million cubic feet burned |
| 3-90-006-30 | Feed and Grain Drying | million cubic feet burned |
| 3-90-006-31 | Food-Drying and Cooking, etc. | million cubic feet burned |
| 3-90-006-32 | Fertilizer Drying | million cubic feet burned |
| 3-90-006-50 | Pulpboard-Dryers | million cubic feet burned |
| 3-90-006-51 | Plywood-Dryers | million cubic feet burned |
| 3-90-006-52 | Pulp-Recovery Boiler | million cubic feet burned |
| 3-90-006-99 | Other/Not Classified | million cubic feet burned |

Process Gas

| | | |
|---|---|---|
| 3-90-007-01 | CO/Blast Furnace | million cubic feet burned |
| 3-90-007-02 | Coke Oven Gas | million cubic feet burned |
| 3-90-007-99 | Other/Not Classified | million cubic feet burned |

Coke

| | | |
|---|---|---|
| 3-90-008-01 | Mineral Wool Furniture | tons burned |
| 3-90-008-99 | Other/Not Classified | tons |

Wood

| | | |
|---|---|---|
| 3-90-009-99 | Other/Not Classified | tons burned |

Liquid Petroleum Gas (LPG)

| | | |
|---|---|---|
| 3-90-010-99 | Other/Not Classified | 1000 gallons burned |

## INDUSTRIAL PROCESS - INPROCESS FUEL

| Other/Not Classified | | SCC Units |
|---|---|---|
| 3-90-999-97 | Specify in Remark | million cubic feet burned |
| 3-90-999-98 | Specify in Remark | 1000 gallons burned |
| 3-90-999-99 | Specify in Remark | tons burned |

## INDUSTRIAL PROCESS - OTHER/NOT CLASSIFIED

| | | |
|---|---|---|
| 3-99-999-99 | Specify in Remark | tons processed |